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Unmanned Aircraft System Propulsion Systems Technology Survey

September 2009

Final Report

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16. Abstract

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LIST OF ACRONYMS

CFR	Code of Federal Regulations
EMI	Electromagnetic interference
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
FC	Fuel cell
NAS	National Airspace System
PEMFC	Proton exchange membrane fuel cell
RATO	Rocket Assist Takeoff
RCV	Rotary cylinder valve
RPE	Reciprocating piston engine
SC	Special Committee
UAS	Unmanned Aircraft System
UAV	Unmanned aviation vehicle

EXECUTIVE SUMMARY

This technology survey is an investigation of various extant and near-future propulsion systems for use in Unmanned Aircraft Systems (UAS). Discussed are existing and near-future propulsion mechanisms of UAS, such as reciprocating piston engines, Wankel rotary engines, gas turbine engines, rocket-powered systems, electric motors, and battery-based systems. Also discussed are systems that use proton exchange membrane fuel cells, photovoltaics, ultracapacitors, and propellers. Each system is described in reference to a larger conceptual framework, with instances and profiles of existing UAS implementing the system being described. Advantages and disadvantages of each type of propulsion system are identified along with associated technical issues and their respective applicability to a UAS context, all of which are described with regard to the concern over regulation and introduction of UAS into the National Airspace System.

1. INTRODUCTION.

Unmanned Aircraft Systems (UAS) have been around for many years, dating as far back as World War II. Since then, a growing interest and use of UAS has been enabled primarily by the advent of fast microprocessors that support intelligent autonomous control of a wide variety of systems—ground, air, and marine. Military use of UAS to gain tactical advantage, paired with an urgent desire to save the lives of soldiers, has been a powerful development-forcing function. However, the commercial use of UAS will likely eclipse the military use, provided that the sense-and-avoid issues associated with UAS operations in the National Air Space (NAS) can be overcome. Pivotal in these systems is the reliable, certifiable use of propulsion systems, which are sized to fit gross vehicle weights ranging from a few ounces to tens of thousands of pounds.

2. PROJECT DESCRIPTION.

2.1 PURPOSE.

This technology survey is an investigation of various extant and near future propulsion systems for use in UAS. Understanding these systems, their characteristics, operation, and salient concepts provides a basis for identifying the technical issues associated with each. Accumulating this information into a single document provides a better perspective for identifying areas of the current state of aircraft regulation, all of which is in anticipation of possibly introducing UAS into the NAS.

2.2 PARENT PROJECT REQUIREMENTS.

As a result of a growing pressure from industry and the foresight to understand the benefits of a paradigm shift, the Federal Aviation Administration (FAA) has expressed interest in assessing and understanding the current state of affairs with regard to UAS. An effect of this interest is the UAS Research Program, which, according to the FAA Fiscal Year 2007 Budget Submission, includes in its goals the following intended outcomes [1]:

> "The UAS research will support FAA regulatory actions and safety oversight needed to ensure the safety of civil UAS operations in the NAS and worldwide. Results of this research program will provide the FAA with the necessary knowledge, tools, and supporting data to take regulatory actions and provide guidance materials for the FAA and UAS industry."

A long-standing tenet of the FAA is that safety is of the utmost importance, and that the way to assert this principle is through comprehensive regulation. A prerequisite to regulating UAS is the understanding of the operation, hardware, environment, and impacts that this technology brings to issue. To accommodate this doctrine of safety with regard to the UAS Technology Survey, the FAA UAS Research Requirements include the following [1]:

> "Conduct a technology survey on designs, operations, and maintenance of Unmanned Aircraft System (UAS) to establish a baseline for the FAA to understand current status of UAS technologies and their safety implications and

perform regulatory gap analysis to identify shortfalls of existing regulations and UAS specific issues."

2.3 GOALS OF SURVEY.

To accommodate the higher-level goals and requirements in a way that is congruent with the intended outcomes, this research had the following goals:

- Identify, explore, and describe existing and near future UAS propulsion systems
- Create a uniform framework for categorizing and recording examples of existing UAS propulsion systems, as well as provide examples and evaluations of UAS implementing each propulsion system under this framework
- Identify the advantages and disadvantages of each UAS propulsion system
- Identify technical issues associated with each UAS propulsion system and discuss applicability to UAS regulation in the NAS
- Create a matrix comparing each UAS propulsion system

2.4 SCOPE OF SURVEY.

While not restricted to these types, this survey focused on the UAS that use propulsion mechanisms that are novel with respect to current manned systems (i.e., focusing less on reciprocating and turbine and more on fuel cell, etc.). Included are propulsion mechanisms that are in use or are anticipated to be in use within the next 2-3 years. Additionally, the goal of this study was not to systematically enumerate through every UAS in existence, but to identify key representative examples of UAS that are demonstrative of the important aspects of each various category.

3. BACKGROUND.

3.1 OVERVIEW OF THE UAS.

A design with the capacity for flight can be accomplished by something as small and simple as a paper airplane. For sustainable, repeatable, and useful flight, however, both a means of propulsion and intelligent control become necessary. Classically, for aircraft, the propulsion mechanism is some sort of engine and the intelligent control is a human pilot. More recently though, modern developments in technology have allowed the intelligent control to be executed without an onboard pilot, resulting in aircraft that can perform repeatable, useful flight—provided that there is a sustainable means of propulsion. Moreover, aside from the capability of useful flight, the ability to circumvent the need for an onboard pilot has stimulated airworthy designs for unmanned systems with greater range in size, weight, design, and control implementations than conventional manned systems. This diversity has entertained interesting applications for various propulsion mechanisms; it is these propulsion mechanisms that are the focus of this survey.

UAS is an evolving concept. Typically, one may think of the acronym UAV, or unmanned aviation vehicle. More recently, the RTCA Special Committee (SC) 203 described the vehicle to be a component of a three-part system in which constituents are identified as segments (figure 1) [2]:

- Aircraft Segment
- Control Segment
- Communications Segment

The segments are seen as composing an entire system, and therefore, the eponymous term Unmanned Aircraft System results.

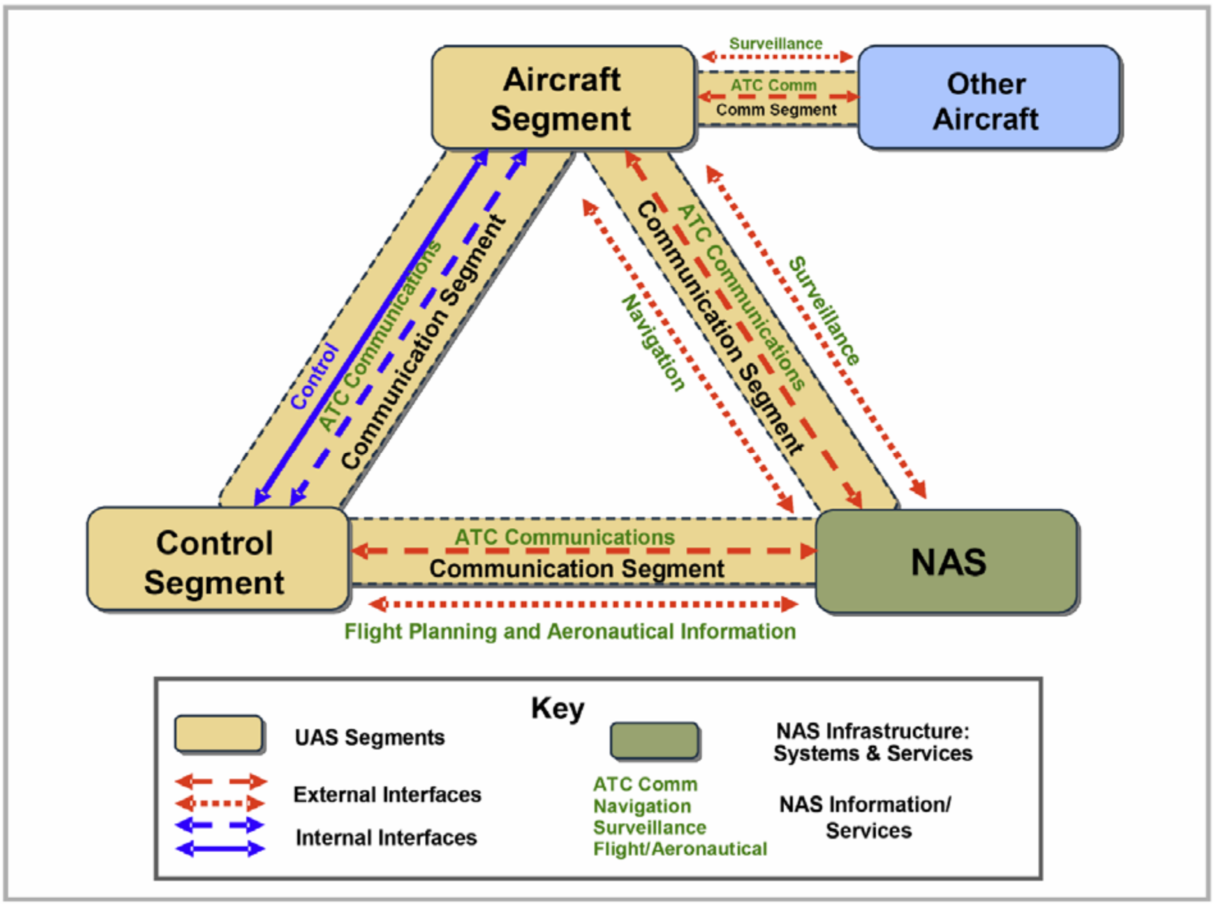


Figure 1. The SC 203 Guidance Material, UAS Segments

The motivation for the system perspective, opposed to the vehicle perspective is one that relates to the issue of communication and control. The ability to control the vehicle transcends the device's capability to function autonomously. Rarely does a manned vehicle perform its duties in complete communication silence; therefore, autonomous aircraft should not be any different. Consequently, the motivation for an essential system perspective is evident, and more specifically, one that includes both communication and control aspects.

3.2 PROPULSION SYSTEMS OVERVIEW.

In most cases, UAS propulsion systems provide vertical lift either directly or by forward motion so that the aircraft may move from place to place (via wings that generate lift). Regardless of the technique, it is important that this propulsion system be reliable, controllable, have sufficient sustainable power to carry itself and its energy source, and have a suitable efficiency for a reasonable amount of endurance.

Variations in operating conditions necessitate that the mechanism of control for any arbitrary propulsion system also be reliable and effective. Loss of control of the propulsion system typically translates into a loss of control of the aircraft. Therefore, examination of a propulsion system should take into account its mechanism for control.

One difficulty associated with discussing each technology individually is reconciling the overlapping aspects of the many examples. Many newer electrically based technologies use a motor, for example, but a fuel cell system may employ a battery, or a photovoltaic system may implement a regenerative fuel cell. Consequently, spotlighting a distinct technology may mistakenly imply exclusion of other technologies (i.e., discussing fuel cell-based systems in a contextual vacuum may implicitly suggest other technologies such as batteries, which are not ever involved). Therefore, the information presented must be organized in a way that does not ignore the overlap, yet does justice to the differentiating factor in each system.

To rectify this, a conceptual framework is offered as a way to abstract the differences of each system and explain how each component fits into a larger generic propulsion system. The perspective in this report takes into consideration that a propulsion system is an assembly of subsystems working together to yield a common, emergent purpose: motion-inducing propulsion. Recognizing the diverse population of propulsion systems used in UAS as being generically composed of instances of the same conceptual units helps to uniformly describe these systems with respect to each other. Moreover, taking this generic angle further may have implications on a modular approach to the certification of these propulsion systems.

In general, these subsystems can be conceptually identified as the following (figure 2):

- An energy source
- An energy transformer
- A powerplant
- A propulsion effecter
- A control effecter

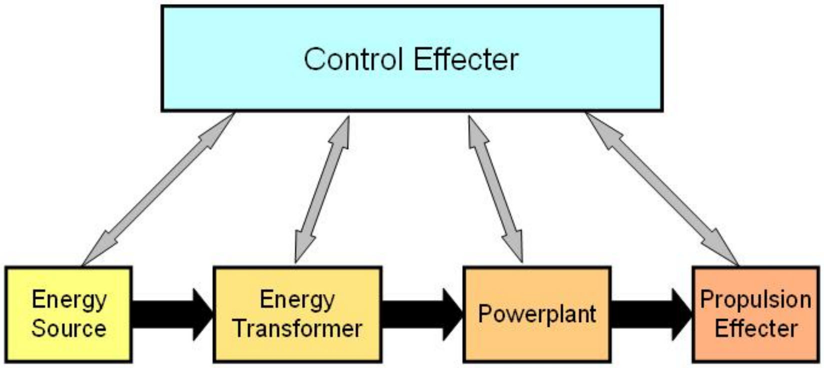


Figure 2. Conceptual Perspective of Propulsion Systems

An energy source is the originating means with which the system will derive its motion. Propulsion requires expenditure of energy, and the energy source is the origin of that energy. Energy source is intended to be a generic label for things like gasoline, diesel fuel, lithium-hydride, liquid hydrogen, solar energy, etc.

An energy transformer converts the potential energy within the energy source into a means for producing work, heat or electrical current. Energy transformer is intended to be a generic label for this conceptual transducer, whose action may yield electrochemically produced electric current, expanding volumes, heat/pressure production, etc.

A powerplant is any aspect that harnesses the product of the energy transformer into motion. For example, a motor that spins a shaft as a result of a supplied electric current classifies as a powerplant in this context. Powerplant is intended to be a generic label for things like a reciprocating engine (with an expanding combustion chamber) or an electric motor (with an electric impulse driver).

A propulsion effecter is the interface between the motion generated and the impulse exerted to move the vehicle; it is what will give the effect of propulsion. Propulsion effecter is intended to be a generic label for things like a propeller (which converts motion into wind) or a turbine nozzle (which converts turbine pressure into high velocity exhaust), as examples.

A control effecter is whatever is in place to give the effect of control to the propulsion-means in a way that serves the purpose of controlling propulsion generation for the vehicle. This wording is chosen to be in distinction from control system, which implies feedback control loops. Control effecter is intended to be a generic label for things that perform control on propulsion such as: a FADEC (Full Authority Digital Engine Control), throttle control, fuel mixture control, or current regulator. Note that control in this context is restricted to the control of the propulsion aspects, not control of the aircraft itself (which may be a superset of the propulsion control aspects).

3.3 THE CODE OF FEDERAL REGULATIONS AND UAS.

UAS present an interesting challenge regarding the application of the Code of Federal Regulations (CFR) as a regulatory standard. While piloted planes must cater to the presence of a human life onboard, a UAS does not. Consequently, they can be lighter, smaller, and may implement designs that benefit from these novel aspects. However, it means the current regulations may need a fortified interpretation. For example, manual overrides for engine controls do not have meaning in a UAS context. Moreover, it is not always the case that a UAS may use conventional propulsion mechanisms such as a reciprocating or turbine engine.

The CFRs are generally written for conventional piston/turbine engines. When considering these regulations as they apply to UAS, the ones that use these conventional engines are not of particular concern. However, because there are UAS powered by unconventional propulsion systems that wish to enter regulated airspace, there is a need for revision in the regulating framework.

3.4 THE NEED FOR REGULATION.

The purpose of regulation is not to arbitrarily impose design constraints, but to provide criteria that guarantees, if followed as specified, will serve as an essential factor in aircraft safety. Other regulations secure safety based on manufacturing process and pilot credentials; the CFRs of interest here ensure that a system will not be unsafe by design. After reviewing 14 CFR Parts 33, 23 subpart E, 27 subpart E, and various other CFRs, some essential principles have been abstracted to demonstrate the possible motivations behind writing the CFRs. This list is not complete and should not serve as a reference; it is intentionally informal. It aims to set the context for the bigger picture of what this survey hopes to assist in: identifying technical issues to help with creating new regulations for UAS. Understanding these principles as derivations of the intent for safe operation illustrates the need for establishing a framework with which to survey and evaluate technical issues.

As interpreted from the CFRs [3], in general:

- Nothing should have a single point of failure, mitigated either by redundancy, backups, or indicator alert mechanisms.
- Important things must not break due to normal usage.
- Things that transfer flammable material cannot be flammable themselves.
- Controls cannot be a single point of failure (loss of control).
- Controls that activate or deactivate things that could be dangerous if done at the worst possible time need to be protected from accidental engagement/disengagement.
- Things that spin must be stoppable at will.
- Things that make exhaust need ventilation.

- Exhaust needs to be appropriately sequestered from fresh air.
- Things that get icy cannot suffocate the engine, and deicing mechanisms need to be reliable.
- Bleed air needs to be appropriately sequestered from normal air.
- Things that get hot need to be cooled in a safe and reliable way.
- Things that can burn need to be kept away from things that get hot.
- Things that can overheat must be able to indicate when in such a state.
- Things that can spill need drains.
- Things that can overfill need unfillable buffer areas.
- Things that can get dirty need filters that do not kill the engine if they get clogged.
- Closed containers need ventilation.
- Things that make sparks need to be separated from things that burn easily.
- Fuel needs to be deliverable (flow) all the time, invariant of environmental conditions.
- Fuel is critical; it needs to be in a stable, strong, and nonthreatened container under all circumstances.
- Important parts need to be accessible and maintainable.
- There need to be mechanisms to preserve engine fluids, but also to keep them from being contaminated or intermingled inappropriately.
- Dangerous external parts need to be visibly self-announcing, and should not be clandestine nor have a misleading appearance of nondanger.
- Moving parts with mass must not vibrate themselves loose or damage the system, in spite of whatever envelope of conditions that might reasonably occur.
- Engines need to be stressed, handled well, and demonstrate the ability to perform safely and reliably under all operating and exceptional conditions (within a reasonable margin).
- Important hardware in a plane must be accessible for safety checks.

The objective is to identify what might motivate the existing regulations to preserve those same underlying concerns when looking at UAS in the NAS. Regarding safety, there is a concept of risk and reducing risk as it relates to risk exposure. For any possible threat, the goal is to not only reduce the likelihood of a critical failure, but also to lessen the severity or criticality of its impact should it occur. The existing CFRs exemplify specific regulation setting guidelines such that, if followed as prescribed, the desired outcome will reduce overall risk exposure to an acceptable level (e.g., 10^{-7} critical failures/hour).

The concern is that many of the UAS that would populate the NAS have technical issues orthogonal to those listed above. For example, regulation stemming from concern of dangerous high-velocity rotations in a turbine or propeller may not be applicable to a 10-lb UAS with a foam propeller. Consequently, this technology survey aims to describe each system, identify characteristic examples, and examine the technical issues associated with each to provide a starting point for taking these new technologies into consideration.

4. SURVEY FRAMEWORK EXPLANATION.

This survey is constructed to explain each propulsion system in general, grounded by applications in specific systems. Presenting the information in a consistent, uniform manner gives a better basis for comparison. The following section explains the format that the material will be presented to guide the reader in understanding the survey.

4.1 DESCRIPTION.

Each propulsion system discussed will include an introductory section that includes an overview or description of the propulsion system and how it works.

4.2 REPRESENTATIVE EXAMPLES EXPLANATION.

This is a listing of some representative UAS that use this type of propulsion as its means of motion. This will include the UAS by name, the manufacturer, and some highlighted specifications of the system as it relates to this topic.

4.3 CATEGORY ADVANTAGES.

This is a listing of the advantages that are gained by using this type of propulsion.

4.4 CATEGORY DISADVANTAGES.

This is a listing of the disadvantages that are encumbered by using this type of propulsion.

4.5 CONCEPTUAL DECOMPOSITION.

Each propulsion system is stratified into its various conceptual components (as described in section 3.2), with each component explained as it relates to the conceptual framework. Table 1 is a template for how the information will be presented for each propulsion system.

Table 1. Template for Conceptual Decomposition of Listed Propulsion Systems

Propulsion System	Conceptual Unit	Description
Propulsion System	Energy source	A description of the energy source conceptual unit
	Energy transformer	A description of the energy transformer conceptual unit
	Powerplant	A description of the powerplant conceptual unit
	Propulsion effecter	A description of the propulsion effecter conceptual unit
	Control effecter	A description of the control effecter conceptual unit

4.6 TECHNICAL ISSUES.

A technical issue is a technology-related issue that, if left unaddressed (i.e., unregulated and/or unmitigated), may increase system and/or environmental risk exposure (likelihood and severity of a critical failure), and is therefore an issue that merits closer examination to either substantiate or dismiss that suspicion. This area delineates some of the most notorious technical issues as they relate to each of the propulsion systems. Table 2 is modeled roughly after a preliminary hazard list, enumerating through all the technical issues associated with each system and describing the applicability of each issue with regard to a UAS context.

Table 2. Template for Listing Technical Issues

Technical Issue	Applicability to UAS Context
First technical issue	Issue as it relates to UAS, risk, safety, regulation and/or the NAS
Second technical issue	Issue as it relates to UAS, risk, safety, regulation and/or the NAS
Third technical issue	Issue as it relates to UAS, risk, safety, regulation and/or the NAS
Etc.	Etc.

5. THE UAS TECHNOLOGY SURVEY: PROPULSION SYSTEMS.

In the following sections, each system is explored as prescribed in the survey framework.

5.1 RECIPROCATING PISTON ENGINES.

5.1.1 Description.

Reciprocating piston systems have a variegated array of implementations. They come in various sizes, geometries, arrangements, and configurations, each with various power, weight, complexity, and efficiency tradeoffs between the alternative arrangements. Often, an engine is classified by how many cylinders it contains, how much total volume is displaced within its cylinders, or the configuration of those cylinders (such as inline, V, and radial configurations).

However, they all contain some variation of the same basic parts, and there is a common principle behind how work is generated from the potential energy stored in its fuel.

A mixture of petroleum distillates and air are pressurized as an enclosure collapses (figure 3). Consequently, the temperature increases with the pressure. An ignition event occurs (for different reasons depending on the thermodynamic cycle used) causing a rapid combustion of the fuel and air mixture. This forces the enclosure to expand with great force, a motion that is translated to a lever-arm mechanism (more specifically, a crankshaft), converting reciprocating motion into rotating motion.

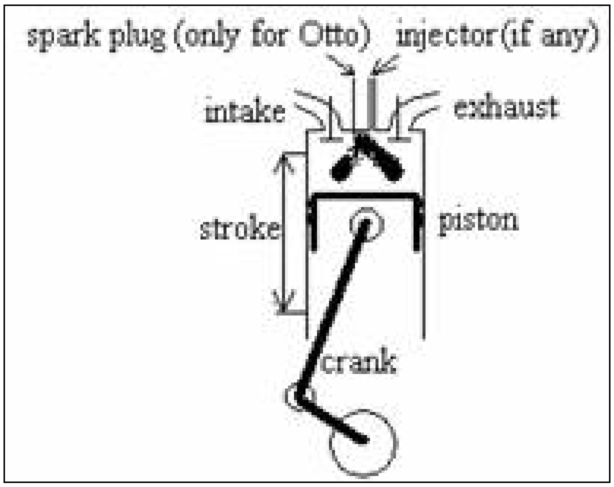


Figure 3. Piston and Combustion Chamber

As the crankshaft turns, it forces another piston down, which then compresses a gaseous mixture of petroleum distillates. This part of the process reinvests work into pressurizing the chambered mixture, only to be reclaimed during the subsequent expansion event. The cycle repeats and is self-sustaining, provided that enough fuel and oxygenated air is supplied, along with proper ignition timing. The rate of this process can be controlled by varying the amount and ratio of reactants (fuel and air).

One issue that manifests with this approach is the perpetually alternating torsional stress on the crankshaft [4]. When a piston is pushed in response to expansion, it applies torque on the crankshaft in one direction, but when the crankshaft later pushes a piston to compress the gaseous mixture in the chamber, the torsion is in the opposite direction. This constant flip-flopping of the crankshaft stresses over long periods can fatigue the shaft, leading to cracks, breakage, and concomitant engine failure.

Vibrational characteristics of a reciprocating piston engine can also cause problems. The engine can shake itself out of mounts, or break apart at high revolutions per minute. In heavy fuel intermittent ignition engines, like a common diesel engine, the high compression ratios can lead to adverse vibrational characteristics that translate all the way through the powertrain to the propeller [4].

Moreover, reciprocating piston engines (RPE) have many pressurized seals that can fail, leading to significant power loss or engine failure. Additionally, if waste heat is not carried away from the engine fast enough, the system can overheat and lead to seizure or fire.

Of all the propulsion systems discussed, Reciprocating Piston Engines is the broadest category, including engines that implement both the Otto and Diesel thermodynamic cycles, as well as four-stroke and two-stroke combustion cycles. Configurations include inline, opposed, and V-configurations. The primary energy source is some sort of refined petroleum distillate, such as gasoline, AVGAS, MOGAS, or heavy fuels like diesel or kerosene [5].

5.1.2 Representative Examples.

Tables 3-7 are examples of RFP application on large, medium, and small UAS.

Table 3. Properties of the General Atomics MQ-1 Predator (RPE) [6]

General Atomics: MQ-1B Predator 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Length 26.7 ft Wingspan 48.7 ft	Propulsion Class	Reciprocating piston engine
Vehicle Gross Weight	2,250 lb	Propulsion Subclass	4-stroke
Payload Data	Capacity 450 lb	Propulsion Unit Make	Rotax 914F
Endurance Range/Time	500 nm/over 24 hrs	Propulsion Unit Weight	Engine: 150 lb
Ceiling	25,000 ft	Power Output	115 hp @ 5800 rpm

Table 4. Properties of the Pioneer UAV RQ-2B Pioneer (RPE) [6]

Pioneer UAV: RQ-2B Pioneer 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Length 14 ft Wingspan 17 ft	Propulsion Class	Reciprocating piston engine
Vehicle Gross Weight	452 lb	Propulsion Subclass	2-cylinder 2-stroke
Payload Data	75-lb capacity	Propulsion Unit Make	Sachs SF 350
Endurance Range/Time	100 nm/5hr	Propulsion Unit Weight	Unavailable
Ceiling	15,000 ft	Power Output	26 hp

Table 5. Properties of the Northrop Grumman RQ-5A Hunter (RPE) [6]

Northrop Grumman: RQ-5A Hunter 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Length 22.6 ft Wingspan 29.2 ft	Propulsion Class	Reciprocating piston engine
Vehicle Gross Weight	1,620 lb	Propulsion Subclass	4-stroke, heavy fuel
Payload Data	200-lb capacity	Propulsion Unit Make	Moto Guzzi
Endurance Range/Time	144 nm/11.6 hr	Propulsion Unit Weight	Unavailable
Ceiling	15,000 ft	Power Output	57 hp (44 kW)

Table 6. Properties of the Insitu ScanEagle (RPE) [7]

Insitu: ScanEagle A 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Length 1.19 m (3.9 ft) Wingspan 3.05 m (10.0 ft)	Propulsion Class	Reciprocating piston engine
Vehicle Gross Weight	40 lb	Propulsion Subclass	1-cylinder, 2-stroke, also heavy fuel variant
Payload Data	Electro-optical or an infrared camera	Propulsion Unit Make	3W-28i, also Sonex Combustion System heavy fuel modification
Endurance Range/Time	15 hr	Propulsion Unit Weight	Engine: 2.67 lb
Ceiling	16,000 ft	Power Output	2.75 hp (2 kW)

Table 7. Properties of the Honeywell MAV (RPE) [8]

Honeywell: MAV 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Diameter 15 in.	Propulsion Class	Reciprocating piston engine
Vehicle Gross Weight	15 lb	Propulsion Subclass	Heavy fuel engine
Payload Data	2-lb capacity	Propulsion Unit Make	RCV 60 cc
Endurance Range/Time	6 nm/40 min	Propulsion Unit Weight	5.5 lb
Ceiling	10,500	Power Output	4.2 bhp @ 8200 rpm

RCV = Rotary cylinder valve

5.1.3 Advantages: RPEs.

The following are typical advantages for RPEs:

- Widely understood technology
  - Benefits for maintenance and reparability
- Diesel engines support use of low volatility heavy fuels
- Potentially lightweight
- Potentially small sizes
- Supports forced-induction for high altitude use

5.1.4 Disadvantages: RPEs.

The following are typical disadvantages for RPEs:

- Vibration and noise
- Many moving parts
- Seal and lubrication requirements
- Cooling requirements
  - Efficiency loss in heat generated
  - Increased complexity
  - Fluid-based cooling systems need to be sealed and liquids separated
  - Adds a weight penalty
- Diesel engine has high compression ratios
  - In-flight restart becomes an issue
  - High transient vibrational characteristics transfers along power train

5.1.5 Conceptual Decomposition.

Based on the proposed concept, RPE decomposition is listed in table 8.

Table 8. Conceptual Decomposition of RPEs

Propulsion System	Conceptual Unit	Description
Reciprocating Piston Engine	Energy source	Petroleum distillates
	Energy transformer	Heat production and expanding volumes resulting from contained combustion of petroleum distillates
	Powerplant	Piston motion resulting from expanding volumes, which in turn, rotate the crankshaft
	Propulsion effecter	Propeller or fan unit driven directly or indirectly (geared) by the crankshaft
	Control effecter	Throttle, regulation of fuel flow

5.1.6 Technical Issues.

The technical issues associated with an RPE are crankshaft weakness, noise, vibration, seals, and high temperature (table 9).

Table 9. Technical Issues of an RPE

Technical Issue	Applicability to UAS Context
Crankshaft Weakness	For engines large enough for manned systems, this is largely covered in the CFRs. The issue here is with smaller engines, where it may be sufficient.
Noise	Noise in manned aircraft interferes with in-flight communication and alerts ground personnel to engine activity. In small UAS, those issues may not apply. However, smaller engines are quieter and may not have loud enough launch personnel alerting volume. However, there is no effect on the nonexistent pilot’s ability to hear in-flight communication.
Vibration	As in manned vehicles, vibration can affect long-term reliability.
Seals	Over time, seals can fail, which leads to power loss and/or potential critical failure.
High Temperature	As in manned vehicles, the engine can fail or seize if heat is not removed from the engine fast enough.

5.2 WANKEL ROTARY ENGINES.

5.2.1 Description.

Like RPEs, Wankel rotary engines use the combustion of petroleum distillates to generate heat and work, and the desired output is the rotation of a power shaft that drives the rest of the system. Wankel rotary engines differ from conventional reciprocating engines in that their volume displacement and associated internal motion occurs in a rotational fashion, as opposed to a back-and-forth manner. An internal triangular core with curved sides (a shape known as a

Reuleaux triangle) divides a chamber with an epitrochoid-shaped stator into three expansion areas (figure 4) [9]. As the core rotates an eccentric shaft (figure 5), the hollowed sides of the curved triangular rotor (figure 6) compress a gaseous volume against the sides of the enclosure. An ignition event occurs, expanding this volume and perpetuating the rotation of the core and shaft and continuing the combustion cycle, generating usable work and waste heat.

Figure 4. Wankel Rotor and Stator

Figure 5. Wankel Rotary Engine Eccentric Shaft

Figure 6. Bathtub Face of Wankel Rotor

A Wankel rotary engine is typically smaller than a reciprocating engine of similar power rating because it has three work-generating expansion events per rotation of the rotor, as opposed to a four-stroke RPE, which only has one per 720° rotation of the crankshaft. However, the shaft turns at triple the rate of the rotor in a Wankel rotary engine, which results in the engine having about twice the power output compared to a four-stroke reciprocating engine for the same combustion volume [9].

The Wankel rotary engine approach has not only a fewer parts count, but also has less overall stress points, resulting in a better reliability factor [10]. Additionally, the net torque through the shaft is always positive, as opposed to the fatigue-inducing torque alternations associated with RPEs [4]. Also, the eccentric shaft shape counterbalances the offset rotor to eliminate a high-speed wobbling, but the high rotation does have a nontrivial gyroscopic effect. A disadvantage of this design is the reduced fuel efficiency, a drawback that has been somewhat lessened as the technology evolves.

5.2.2 Representative Examples.

Tables 10 and 11 show two examples of Wankel rotary engines.

Table 10. Properties of the AAI RQ-7A Shadow 200 (Wankel Rotary Engine) [6]

AAI: RQ-7A Shadow 200 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Length 11.2 ft Wingspan 12.8 ft	Propulsion Class	Wankel rotary engine
Vehicle Gross Weight	327 lb	Propulsion Subclass	Single rotor
Payload Data	60-lb capacity	Propulsion Unit Make	UEL AR-741, 208 cc
Endurance Range/Time	68 nm/5 hr	Propulsion Unit Weight	Engine: 23.5 lb
Ceiling	14,000 ft	Power Output	38 bhp @ 7800 rpm

Table 11. Properties of the Sikorsky Cypher (Wankel Rotary Engine) [6]

Sikorsky: Cypher 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Diameter 6.5 ft	Propulsion Class	Wankel rotary engine
Vehicle Gross Weight	250 lb	Propulsion Subclass	Single rotor
Payload Data	50-lb capacity	Propulsion Unit Make	UEL AR-801, 294 cc
Endurance Range/Time	36 nm/3 hr	Propulsion Unit Weight	Engine: 43 lb (cf. AR-801 spec. sheet)
Ceiling	8000 ft	Power Output	40 bhp @ 6000 rpm 51 bhp @ 8000 rpm

5.2.3 Category Advantages.

The advantages of the Wankel rotary engine are:

- Higher power output for similar displacement
- Iron rotor in aluminum housing reduces likelihood of engine seizure
- Lighter weight than legacy or compression-ignition engines
- Much quieter than reciprocating engines
- Lower vibration than reciprocating engines
- The most reduced parts count of any light aircraft engine. This relates to no valves, no heavy crankshaft, or lighter propellers because of rotation vice reciprocation and much longer time between overhaul of the engine.
- Overhaul cost is greatly reduced.
- Reliability expected to approach turbine standards.
- FADEC or DEM (Digital Engine Management) accounts for reduced fuel consumption to at or better than legacy engines.

5.2.4 Category Disadvantages.

The disadvantages of the Wankel rotary engine are:

- Liquid-cooled engine adds to weight and complexity, failure modes
- 50% higher fuel consumption than comparable diesel engines
- Higher electromagnetic and thermal signatures compared to diesel engine
- Limited information concerning technical success of Wankel rotary engines
- Potential difficulty meeting emission standards

5.2.5 Conceptual Decomposition.

Based on the proposed concept, the Wankel rotary engine can be decomposed, as shown in table 12.

Table 12. Conceptual Decomposition of a Wankel Rotary Engine System

Propulsion System	Conceptual Unit	Description
Wankel Rotary Engine	Energy source	Petroleum distillates' internal energy relative to oxidation products
	Energy transformer	Heat production and expanding volumes resulting from contained combustion of petroleum distillates
	Powerplant	Reuleaux triangular rotor motion within an epitrochoid stator turning the eccentric shaft
	Propulsion effecter	Propeller or fan unit driven directly or indirectly (geared) by eccentric shaft
	Control effecter	FADEC, carburetor, fuel/air flow control

5.2.6 Technical Issues.

The technical issues associated with rotary engine systems are exhaust temperature, compression seals, engine cooling and oil burn-off (table 13).

Table 13. Technical Issues of a Wankel Rotary Engine System

Technical Issue	Applicability to UAS Context
Exhaust Temperature	High exhaust temperatures of a rotary engine can be a threat to surrounding components, and increases risk of fire. Moreover, the materials to make the exhaust must be able to handle the higher temperatures, which are more expensive and difficult to work with than regular exhaust material.
Seals (compression issues)	The mechanics of a rotary engine leads to seal reliability issues related to compression loss, resulting in the potential for lost power.
Engine Cooling	Compact design more difficult to cool, idling at high temperatures can be an issue.
Oil Burn-Off	Due to the seal configuration, as the engine operates, a small amount of oil burns off. This may limit UAS range without sufficient oil reserves or other mitigation.

5.3 PROPELLER-BASED SYSTEMS.

5.3.1 Description.

Propellers have a large existing body of knowledge that is outside the scope of this document. However, as they are an important instance of commonly used propulsion effecter, they deserve mention. Most reciprocating piston and rotary engines use propellers are their propulsion effecters, and many smaller UAS that depend on electrically based propulsion technology use an electric motor, which drives a propeller. A major advantage of propellers is that they are simple enough that they can be scaled for use in smaller UAS, and they are coupled to small motors in electrically based UAS.

Propellers operate on the same principle as a wing in that each blade that passes through the air generates forward-directed, motion-inducing lift, called thrust. The propeller translates spinning motion from a powerplant into the controllable forward motion of the UAS (figure 7).

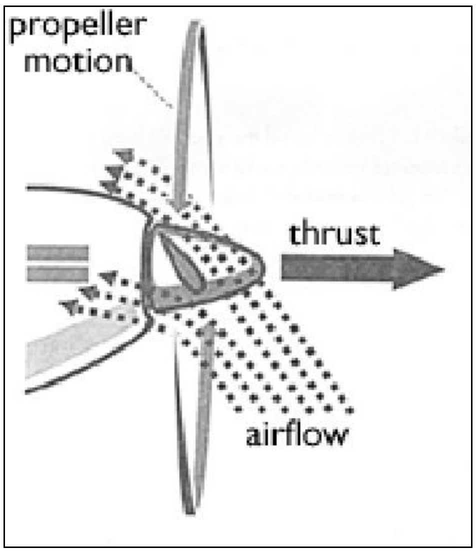


Figure 7. Propeller-Generated Thrust

In smaller UAS, the propellers may not need to have the same restrictions as large propellers. For example, even at full speed, sticking your finger into a moving tiny plastic or foam propeller on a UAS may be harmless. (Consequently, with small UAS, the regulation on that may be more flexible compared to manned vehicles). Also, there is a scaling issue. Smaller propellers may behave differently or be susceptible to different threats than larger propellers. Whereas a large propeller may destroy an object that inadvertently finds its way into the spin path, a propeller on a smaller UAS may be destroyed and/or completely removed from the aircraft as a result of a foreign object strike.

5.3.2 Representative Examples.

Table 14 shows the properties of the propeller.

Table 14. Properties of the Propeller

Propulsion Effecter: Propeller			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Unspecified	Propulsion Class	Unspecified
Vehicle Gross Weight	Unspecified	Propulsion Subclass	Unspecified
Payload Data	Unspecified	Propulsion Unit Make	Unspecified
Endurance Range/Time	Unspecified	Propulsion Unit Weight	Unspecified
Ceiling	Unspecified	Power Output	Unspecified

5.3.3 Category Advantages.

The advantages of propeller-based systems are:

- Low engineering overhead
- Simpler control effecter (adjustments in speed and blade pitch) than a gas turbine engine
- Inexpensive compared to more complex thrust-based systems
- Propeller systems tend to have a quicker reaction to control changes than a gas turbine systems

5.3.4 Category Disadvantages.

The disadvantages of propeller-based system are:

- Strike hazard to personnel or objects in the environment
- Efficiency variations at different rotation speeds
- Rotation speed limited to about 2500 rpm by inefficiencies when the blade tips go supersonic
- Vibration sensitivities (subject to cracks)

5.3.5 Conceptual Decomposition.

Based on the proposed concept, propeller-based systems can be decomposed, as shown in table 15.

Table 15. Conceptual Decomposition of a Propeller-Based System

Propulsion System	Conceptual Unit	Description
Electric Motor	Energy source	Unspecified
	Energy transformer	Unspecified
	Powerplant	Unspecified
	Propulsion effecter	A propeller
	Control effecter	Shaft rotation, blade pitch control

5.3.6 Technical Issues.

The technical issues associated with a propeller-based system are strike hazard, efficiency, noise, and vibration (table 16).

Table 16. Technical Issues of a Propeller-Based System

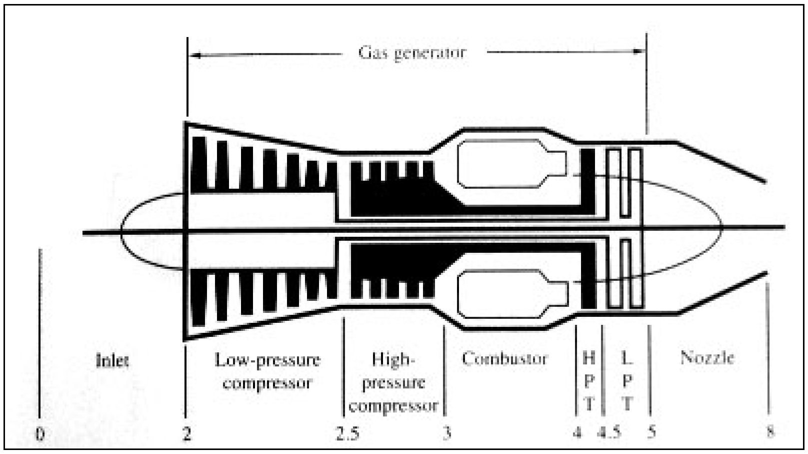
Technical Issue	Applicability to UAS Context
Strike Hazard	Larger UAS are similar to manned systems with regard to strike hazard, but smaller UAS may not need to be subject to the same strict requirements, as the propellers are not as dangerous.
Efficiency	In-flight adjustable propeller pitch.
Noise	In a manned system, propellers are noisy. In smaller UAS, the propeller is smaller and therefore quieter.
Vibration	As with manned systems, vibration can be an issue with propellers used in UAS, particularly larger UAS. Cracking and fatigue can result from transient and long-term vibration.

5.4 GAS TURBINE ENGINES.

5.4.1 Description.

A gas turbine engine is an internal combustion engine operating on a highly dynamic process, investing work to process air and fuel in a way that yields high-velocity output thrust as the return on investment. A gas turbine engine comes in various forms, and the three described in particular are the jet turbine engine, turbofan engine, and turboprop engine.

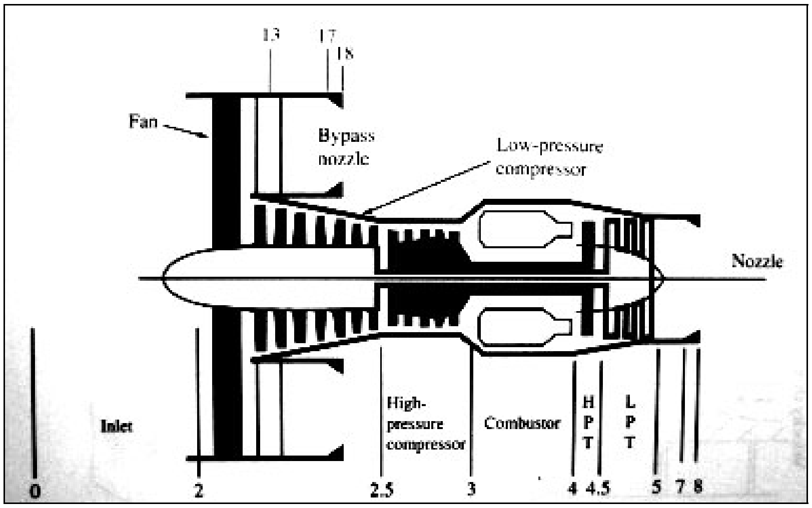
A functioning jet turbine engine has a series of internal fans that spin at a high velocity, which successively compress inhaled air as it progresses towards a combustion area (figure 8). This highly pressurized air is mixed with heavy petroleum distillate fuel and burned, an event that liberates heat and dramatically increases the already high pressure [11]. The geometry of a jet turbine engine is such that the high-pressure reaction product manifests externally as high-velocity exhaust particles, creating thrust in a momentum exchange as a demonstration of Newton's Third Law of Motion. Some of the high-energy exhaust is sapped to drive the turbine that compresses the incoming air, investing work up front to be reclaimed later [11]. This process produces much waste heat that is lost, negatively impacting the efficiency.



HPT = High-pressure turbine
LPT = Low-pressure turbine

Figure 8. Turbojet Engine Schematic

While perhaps a low-resolution description of a jet turbine, the point is that, conceptually, the energy content of the products (air and fuel) versus the reactants (exhaust) is extracted to produce motion in a controllable reaction. However, the direct jet approach has enough efficiency drawbacks that, in some applications, a turbofan is more appropriate. A turbofan works on a similar principle as a jet turbine, except that more work is sapped from the high-energy exhaust gas to drive a fan mechanism, trading off some direct thrust for additional fan-driven thrust (figure 9) [11]. A turboprop engine operates on a similar principle as a turbofan, except that instead of a fraction, almost all of the high-energy output is used to drive a turbine that is gear coupled to a propeller. A turboshaft is similar to the turboprop except that the power is supplied to a shaft rather than a propeller (used extensively for rotorcraft) [11].



HPT = High-pressure turbine
LPT = Low-pressure turbine

Figure 9. Turbofan/Turboprop Engine Schematic

Gas turbine engines are field tested and proven reliable propulsion mechanisms, but are classically very large and heavy. Modern developments have yielded the new concept of microturbine engines, which are gas turbine engines small enough to be held by a single person and produce thrust outputs on the order of tens of pounds [12]. While instances exist of UAS that implement each previously mentioned variant of the gas turbine engine, there are no known examples of small UAS that use a microturbine engine. However, industry manufacturers have acknowledged the potential of microturbine engines for UAS applications and have responded accordingly.

5.4.2 Representative Examples.

Examples of gas turbine engines are shown in tables 17-20.

Table 17. Properties of the Bombardier CL-289 (Gas Turbine) [13]

Bombardier: CL-289

UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Wingspan 4.3 ft	Propulsion Class	Gas turbine engine
Vehicle Gross Weight	650 lb	Propulsion Subclass	Turbojet
Payload Data	75 lb-capacity	Propulsion Unit Make	KHD T117
Endurance Range/Time	108 nm/0.5 hr	Propulsion Unit Weight	Engine: 51 lb (23 kg)
Ceiling	3900 ft	Power Output	236-lb thrust

Table 18. Properties of the Northrop Grumman RQ-4A Global Hawk (Gas Turbine) [6 and 14]

Northrop Grumman: RQ-4A Global Hawk

UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Length 44.4 ft Wingspan 116.2 ft	Propulsion Class	Gas turbine engine
Vehicle Gross Weight	26,750 lb	Propulsion Subclass	Turbofan
Payload Data	1,950-lb capacity	Propulsion Unit Make	Rolls Royce AE-3007H
Endurance Range/Time	5,400 nm/32 hr	Propulsion Unit Weight	Engine: 1,586 lb
Ceiling	65,000 ft	Power Output	8,290-lb thrust

Table 19. Properties of the General Atomics Predator B (Gas Turbine) [6]

General Atomics: Predator B 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Wingspan 66 ft	Propulsion Class	Gas turbine engine
Vehicle Gross Weight	10,000 lb	Propulsion Subclass	Turboprop
Payload Data	800-lb internal capacity 3,000-lb external capacity	Propulsion Unit Make	TPE-331-10T
Endurance Range/Time	30+ hr	Propulsion Unit Weight	Unavailable
Ceiling	50,000 ft	Power Output	700 shp

Table 20. Properties of the MicroJet FX Series (Gas Turbine) [12]

MicroJet: FX Series 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	N/A	Propulsion Class	Small gas turbine
Vehicle Gross Weight	N/A	Propulsion Subclass	Turbojet
Payload Data	N/A	Propulsion Unit Make	FXR30 (this example)
Endurance Range/Time	N/A	Propulsion Unit Weight	Engine: 3.5 lb
Ceiling	N/A	Power Output	32-lb static @ 115000 rpm

5.4.3 Category Advantages.

The advantages of gas turbine engines are:

- High power density
- Tremendous thrust capability
- Not limited by sound barrier like the tips of propeller blades
- Decent efficiency at 30% load
- Insensitivity to fuel quality
- Can use of air bearings eliminate need for auxiliary lubricating fluid or oil

5.4.4 Category Disadvantages.

The disadvantages of gas turbine engines are:

- Expensive
- Loud
- Jet wash
- Complexity
- Very high velocity rotation
- High internal temperatures

5.4.5 Conceptual Decomposition.

Based on the proposed concept, gas turbine engines can be decomposed, as shown in table 21.

Table 21. Conceptual Decomposition of a Gas Turbine System

Propulsion System	Conceptual Unit	Description
Gas Turbine Engine	Energy source	Petroleum distillates
	Energy transformer	Heat production and extremely high pressures (relative to operating environment) resulting from contained combustion of petroleum distillates
	Powerplant	Dynamic adiabatic/isentropic one of those processes of high-pressure gas converting to high-velocity gas from nozzle
	Propulsion effecter	High-velocity gas exiting the rear aperture
	Control effecter	Fuel flow, propeller pitch

5.4.6 Technical Issues.

The technical issues associated with a gas turbine engine are high energy rotation, high temperature, blade balance and vibration, blade wear, blade cooling, bearing wear (table 22).

Table 22. Technical Issues of a Gas Turbine System

Technical Issue	Applicability to UAS Context
High Energy Rotation	As in manned systems, the high energy rotation of the turbine makes it such that certain critical failures can lead to complete self destruction of the system.
High Temperature	As in manned systems, high operating temperature increases risk of fire.
Blade Balance and Vibration	As in manned systems, blade imbalance magnified by the high velocity rotation can lead to vibration that will reduce long-term reliability, and increase risk of system failures.
Blade Wear	As in manned systems, high energy rotation of the engine internals can cause system damage if a foreign object is sucked in during operation. Blade warping can lead to vibration and cascading failure.
Blade Cooling	As in manned systems, if the turbine blades are not cooled, they may warp and lead to imbalance.
Bearing Wear	As in manned systems, if the bearings are not properly cooled and/or lubricated, they can wear, leading to vibration and instabilities.

5.5 ROCKET PROPULSION.

5.5.1 Description.

According to the "Rocket and UAV Systems Handbook,"

> "Rocket systems are self-contained flight vehicles, which carry their fuel and oxidizer internally and boost their payloads to high velocity. After burnout, the payload continues on an unpowered, ballistic trajectory either into orbit or to a target on earth. Depending on its range and trajectory, a rocket may or may not leave the atmosphere. Rocket systems normally consist of four elements: 1) the payload, or warhead; 2) a propulsion system, which provides the energy to accelerate the payload to the required velocity; 3) a guidance and control system, which guides the rocket along a preprogrammed trajectory to its destination (not all rockets are guided, however); and 4) an overall structure that holds everything together." [15]

The focus here is that the propulsion system "provides the energy to accelerate the payload to the required velocity." A rocket is propelled by a chemical reaction that generates extreme pressure gradients and high-velocity particles that exit a nozzle. The resulting momentum exchange provides impulse over some duration, accelerating the rocket's mass [16].

With rockets, it is often important that as much of the energy stored in the propellant ends up as kinetic energy of the body of the rocket as possible, with as little as possible wasted in the exhaust jet [16]. In common with many jet-based engines, rockets are extremely inefficient at low speeds due to their high and typically fixed exhaust speed. There, the exhaust carries away a huge amount of kinetic energy rearward. As speeds rise, the resultant exhaust speed goes down, and thus energetic efficiency rises, reaching a peak of (theoretically) 100% when the vehicle is traveling exactly at the same speed that the exhaust is emitted. Then, the exhaust in principle stops dead in space behind the vehicle. The efficiency then drops off again at even higher speeds, as the exhaust ends up traveling forward behind the vehicle. These energy considerations mean that rockets are mainly useful when a very high speed is required, and thus, they are rarely if ever used for general aviation [16]. Jet engines that have a better match between speed and exhaust velocity, such as turbofans, predominate for atmospheric use.

Propulsion derived exclusively from rocket power tends to be used in applications where the asset is not expected to return home. However, for use in a UAS, it is more likely to see rocket power as a means of takeoff assist, such as in the RQ-2B Pioneer (see figure 10 and table 4).

Figure 10. Rocket Assist in RQ-2B Pioneer

5.5.2 Representative Example—Lockheed Martin Cormorant Project.

The Cormorant project is a risk-reduction investigation in UAS technology that may implement rocket power not necessarily for the primary means of propulsion, but instead for Rocket Assist Takeoff (RATO) [6], as shown in table 23.

Table 23. Properties of the Lockheed Martin Cormorant (Rocket Assist) [6]

Lockheed Martin: Cormorant Project 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Length 19 ft Wingspan 16 ft	Propulsion Class	TBD
Vehicle Gross Weight	9,000 lb	Propulsion Subclass	TBD
Payload Data	1,000 lb	Propulsion Unit Make	TBD
Endurance Range/Time	400-500 nm/ 3 hr	Propulsion Unit Weight	TBD
Ceiling	35,000 ft	Power Output	3,000-lb thrust rocket-boosted takeoff

5.5.3 Category Advantages.

The advantages of rocket propulsion systems are:

- High power density
- Mature, with long history of operation
- Self-contained energy source for use in low-oxygen environments

5.5.4 Category Disadvantages.

The disadvantages of rocket propulsion systems are:

- Inefficiencies at low speeds
- High rate of fuel usage; low endurance
- Complex control system
- Expensive guidance components

5.5.5 Conceptual Decomposition.

Based on the proposed concept, rocket propulsion systems can be decomposed, as shown in table 24.

Table 24. Conceptual Decomposition of a Rocket Propulsion System

Propulsion System	Conceptual Unit	Description
Rocket Propulsion	Energy source	Self-contained chemical reactants (solid or liquid)
	Energy transformer	Exothermic high-pressure chemical reaction in rapid release of kinetic energy
	Powerplant	Expulsion of reaction products through nozzle creating high-velocity exhaust
	Propulsion effecter	Thrust from momentum transfer of high-velocity exhaust
	Control effecter	Nozzle direction, reaction rate control

5.5.6 Technical Issues.

The technical issues associated with rocket propulsion are explosion, fire, and propellants (table 25).

Table 25. Technical Issues of a Rocket Propulsion System

Technical Issue	Applicability to UAS Context
Explosion	Possibility of explosion is an issue; more relevant in civilian applications
Fire	Possibility of explosion is an issue; more relevant in civilian applications
Propellants	Chemistry and materials used as propellants can be an issue

5.6 ELECTRIC MOTOR-BASED SYSTEMS.

5.6.1 Description.

Electric motors serve as powerplants to create rotational motion from electric power. For electrically based propulsion systems, electric motors are used as the powerplant because they can be easily coupled with propellers as the propulsion effecter; all that is needed is a continuous source of electricity.

Motors and generators consist of two basic entities: the field magnet, called a stator (nonmoving) and the armature, called the rotor. Magnetic material (such as iron) is used in the rotor, and the stator concentrates magnetic field flux density. Field laminations (thin, insulated layers of iron) decrease undesirable (heat producing) eddy current losses (from same induction that causes the desirable rotation). The rotational speed of an electric motor is proportional to the voltage applied to it, and the torque is proportional to the current. Electric motors range from very large to very small. A cut-away view of a small electric motor is shown in figure 11 [17].

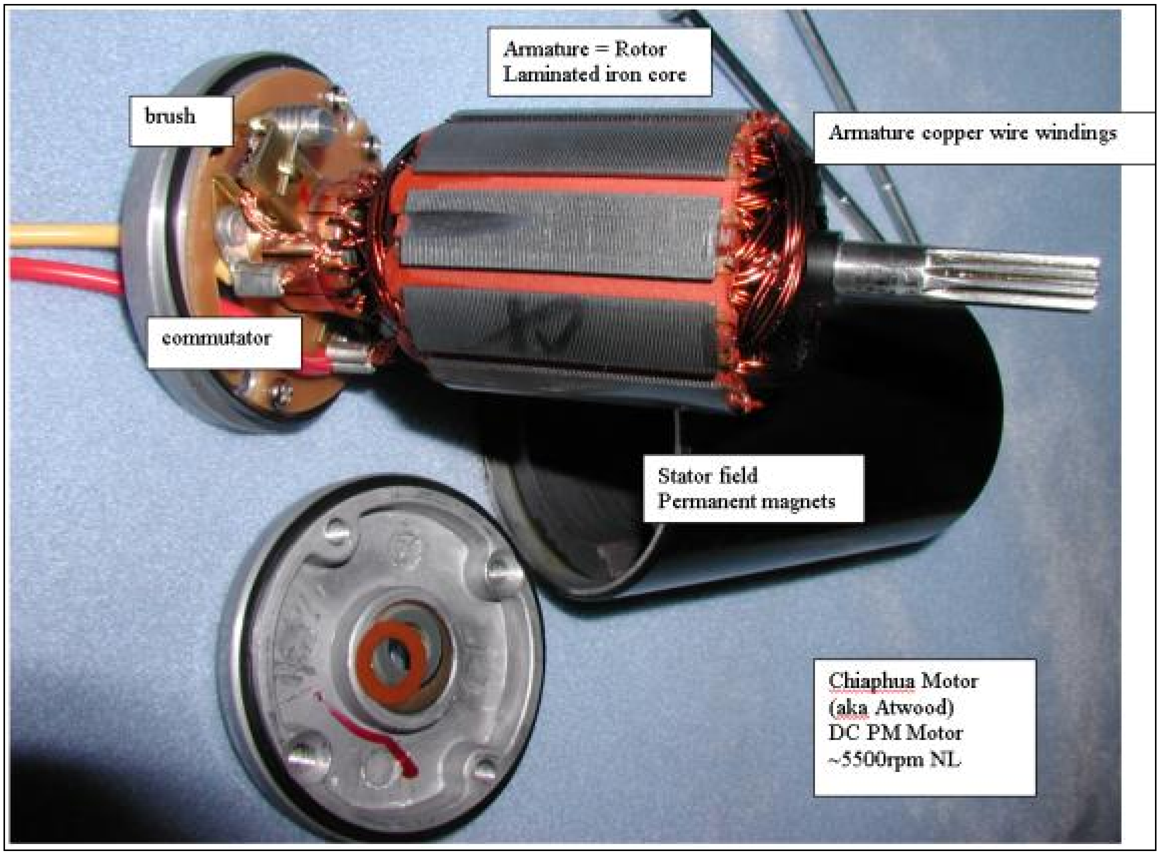


Figure 11. Cut-Away View of Small Electric Motor

Electric motors are universal in usage, widely understood, simple in concept and operation, low cost due to economies of scale, and very easy to obtain. With regard to small (or large) electrically based UAS propulsion applications and technical issues, the concern is less over the electric motor and more over a consistent, sustainable, reliable electric power source with sufficient endurance to power the electric motor.

5.6.2 Representative Examples.

While almost any electrically based UAS uses an electric motor as its propulsion effecter, few manufacturers readily and/or willingly publish information on the specifications of the motor. Table 26 shows a rare instance in which information has been provided on the motor.

Table 26. Properties of the AC Propulsion SoLong (Electric Motor) [18 and 19]

<table>
<tr><td colspan="4">AC Propulsion: SoLong
</td></tr>
<tr><td colspan="2">UAS Characteristics</td><td colspan="2">Propulsion Characteristics</td></tr>
<tr><td>Vehicle Dimension</td><td>Wingspan 4.75 m</td><td>Propulsion Class</td><td>Electric Motor</td></tr>
<tr><td>Vehicle Gross Weight</td><td>12.6 kg (28 lb)</td><td>Propulsion Subclass</td><td>DC motor</td></tr>
<tr><td>Payload Data</td><td>Unavailable</td><td>Propulsion Unit Make</td><td>Kontronik Tango 45-06 3-phase, brushless, ironless motor with 4.2:1 planetary gear reduction</td></tr>
<tr><td>Endurance Range/Time</td><td>48+ hr</td><td>Propulsion Unit Weight</td><td>300 g</td></tr>
<tr><td>Ceiling</td><td>8000 m</td><td>Power Output</td><td>Max motor power 800W</td></tr>
</table>

5.6.3 Category Advantages.

The advantages of electric motor-based systems are:

- Electrically powered
- Low maintenance
- Reliable
- Robust
- Less issues surrounding overheating as opposed to thermodynamic engines
- High torque
- Scalability
- Quiet

5.6.4 Category Disadvantages.

The disadvantages of electric motor-based systems are:

- Electromagnetic interference
- Requires large currents
- Potential sensitivity to water and other conductive liquids

5.6.5 Conceptual Decomposition.

Based on the proposed concept, the electric motor-based system can be decomposed, as shown in table 27.

Table 27. Conceptual Decomposition of an Electric Motor-Based System

Propulsion System	Conceptual Unit	Description
Electric motor	Energy source	Unspecified
	Energy transformer	That which yields electrical power
	Powerplant	An electric motor
	Propulsion effecter	Unspecified; usually a propeller or fan unit that is functioning as a result of the rotating motion created by the motor. Alternatively, for example, it could drive a wing-flapping mechanism.
	Control effecter	Feedback control loops, current/voltage control

5.6.6 Technical Issues.

The technical issues of an electrical motor-based system are electromagnetic interference (EMI), sparking, and corrosion (table 28).

Table 28. Technical Issues of an Electric Motor-Based System

Technical Issue	Applicability to UAS Context
EMI	Transients and noise generated by the electromagnetic activity during motor operation, start, and stop can interfere with UAS electronics and communication devices.
Sparking	Motor provides ignition source; potential problem in hydrogen-based UAS operating an electric motor.
Corrosion	High current densities can corrode terminals.

5.7 BATTERY-BASED SYSTEMS.

5.7.1 Description.

Batteries are electrochemical storage devices that serve as vessels for a reversible chemical reaction. Composed of cells, they do not require fuel or oxygen; they are self-contained units whose potential energy is only liberated when a load is applied across the terminals. In general, it consists of one or more voltaic cells, each of which is composed of an anode and cathode connected in series by the conductive electrolyte (figure 12).

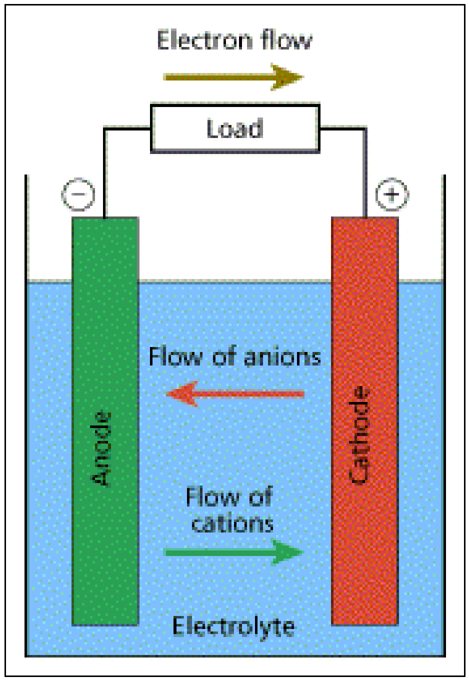


Figure 12. Generic Battery

There are different types of batteries for UAS applications. Rechargeable batteries are preferred and therefore the focus of discussion. NiCad and metal-hydrides are typically used, but modern technology has introduced lithium-based battery technology [20]. Lithium is low on the periodic table, is the lightest elemental solid, is a powerful reducer, and has very low electronegativity. Lithium batteries tend to be lighter and have higher-energy density per unit mass than other self-contained energy storage systems [21]. To date, the most economical battery is the basic cylindrical 18,650 (18 mm diameter with 650 mm length), with a capacity of 2,000mAh [20]. New variations in chemistries and crystalline structures (such as polymers, hydrides, gels, new crystalline structures, and exotic doping materials) are leading to ever-improving battery technology [20].

A significant issue with batteries relates to the recharge and discharge rate. Batteries have a wide dynamic range of behavior in various temperature conditions, and behave best when operating at their preferred operating temperature. High current loads can overheat batteries due to internal resistance, and a short circuit can cause deformation or bursting from rapid gas formation [20].

Lithium ion batteries are a type of rechargeable battery commonly used in consumer electronics. They are currently one of the most popular types of battery, with one of the best energy-to-weight ratios, no memory effect, and a slow loss of charge when not in use. In reference 21, lithium batteries are discussed in detail:

> "A lithium-ion gel polymer battery power supply system can operate a UAV for over 150 flights. A lithium-based secondary battery system provides the combined benefits of rechargeability and an inherently safer chemistry over a

primary battery system. As secondary lithium-based battery systems evolve further, leak-proof, conformable true polymer batteries may be a reality, which will increase the margin of safety even further and provide flexibility in positioning the battery on crafts where volume is a major constraint."

5.7.2 Representative Examples.

Tables 29-32 show examples of battery-based systems.

Table 29. Properties of the EMT Aladin (Battery) [23]

EMT: Aladin 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Wingspan 4.9 ft	Propulsion Class	Battery
Vehicle Gross Weight	6.6 lb	Propulsion Subclass	Unavailable
Payload Data	Unavailable	Propulsion Unit Make	Unavailable
Endurance Range/Time	6 nm/1 hr	Propulsion Unit Weight	Unavailable
Ceiling	500 ft	Power Output	Unavailable

Table 30. Properties of the AeroVironment Wasp (Battery) [6]

AeroVironment: Wasp

UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Length 8 in. Wingspan 13 in.	Propulsion Class	Battery
Vehicle Gross Weight	0.4 lb	Propulsion Subclass	Proprietary
Payload Data	0.1-lb capacity daylight cameras with real time video downlink	Propulsion Unit Make	Proprietary
Endurance Range/Time	5 nm/60 min	Propulsion Unit Weight	Proprietary
Ceiling	1200 ft	Power Output	Proprietary

Table 31. Properties of the Lockheed Martin Desert Hawk (Battery) [24]

Lockheed Martin: Desert Hawk

UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Length 34 in. Wingspan 52 in.	Propulsion Class	Battery
Vehicle Gross Weight	3.5 kg (7 lb)	Propulsion Subclass	Unavailable
Payload Data	Color CCD or infrared cameras	Propulsion Unit Make	Unavailable
Endurance Range/Time	6 nm/1 hr	Propulsion Unit Weight	Unavailable
Ceiling	500 ft	Power Output	Unavailable

Table 32. Properties of the ARA BATCAM (Battery) [6]

ARA: BATCAM 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Length 24 in. Wingspan 21 in.	Propulsion Class	Battery
Vehicle Gross Weight	0.84 lb	Propulsion Subclass	Unavailable
Payload Data	0.09-lb capacity	Propulsion Unit Make	Unavailable
Endurance Range/Time	1.6 nm/ 18 min	Propulsion Unit Weight	Unavailable
Ceiling	1000 ft	Power Output	Unavailable

BATCAM = Battlefield Air Targeting Camera Micro Air Vehicle

5.7.3 Category Advantages.

The advantages of battery-based systems are:

- Silent
- Lightweight
- Efficient (reduced levels of waste heat)
- No waste products
- Self-contained
  - No external reactants required
  - Reduced complexity
- No moving parts
- Rechargeable
- Uses electric motor as the prime mover. Has advantages, including reliability, maintenance, control, and high-altitude operational benefits.

5.7.4 Category Disadvantages.

The disadvantages of battery-based systems are:

- Limited endurance
- Battery recharge

  - Delays due to current limits and recharge rates
  - Heating associated with rapid recharge
  - Battery discharge may be efficient, but recharge process is inefficient

- Heating do to internal resistance
- Performance sensitivity to environmental temperature conditions
- Hazardous chemicals (corrosive internal chemistry)

5.7.5 Conceptual Decomposition.

Based on the proposed concept, battery-based systems can be decomposed, as shown in table 33.

Table 33. Conceptual Decomposition of a Battery-Based System

Propulsion System	Conceptual Unit	Description
Battery-Based System	Energy source	Electrochemical energy gradient between internal cathode/anode materials
	Energy transformer	Chemical reaction yielding electron transport, generating an electromotive force
	Powerplant	Electrically driven motor
	Propulsion effecter	Propeller or fan unit driven directly or indirectly (geared) by motor shaft
	Control effecter	Voltage/current regulators, analog/digital feedback control loops

5.7.6 Technical Issues.

The technical issues of a battery-based system are endurance, recharge/discharge rate, operating temperature sensitivity, hazardous chemicals, and long-term reliability (table 34).

Table 34. Technical Issues of a Battery-Based System

Technical Issue	Applicability to UAS Context
Endurance	Endurance of batteries changes over the life of battery. So, the issue is where to set the margin of safety for duration of flight to avoid the risk of unexpected failure/loss of power.
Recharge/Discharge Rate	High current may dangerously overheat system, leading to burst or indeterminate internal states
Operating Temperature Sensitivity	Undeterministic behavior due to unexpected environmental conditions
Hazardous Chemicals	Risk of leakage damaging local components, leading to critical failure
Long-Term Reliability	Risk of unexpected failure due to shortened lifespan over time

5.8 PROTON EXCHANGE MEMBRANE FUEL CELL.

5.8.1 Description.

A fuel cell derives usable power from supplied chemical reactants in the form of an electric current. Unlike consuming oxygen in the direct combustion of fuel, a fuel cell consumes oxygen (or some other environmentally provided reactant) to generate electrical power an electrochemical process. There are a wide variety of fuel cells, including proton exchange membrane, phosphoric acid, molten carbon, solid oxide, methanol, and alkaline [5 and 25].

To date, the proton exchange membrane fuel cell (PEMFC) is the most promising technology for use in UAS propulsion systems, and therefore will be the only fuel cell variant discussed. As shown in figure 13, molecular hydrogen is exposed to a platinum catalyst. The catalyst causes the hydrogen to ionize into its constituent protons and electrons. A curious property of the electrolytic membrane separating the anode and cathode is that it excludes other particles, allowing only the protons (hydrogen stripped of its electron shell) to pass through. At the cathode, oxygen combines with the protons in an electrochemical oxidation process, requiring electrons. This draws the electrons liberated in the anode across a load; the current produced can be used as a source of power. This power source can be electrically superpositioned in stacks to increase voltage and current delivery characteristics [26].

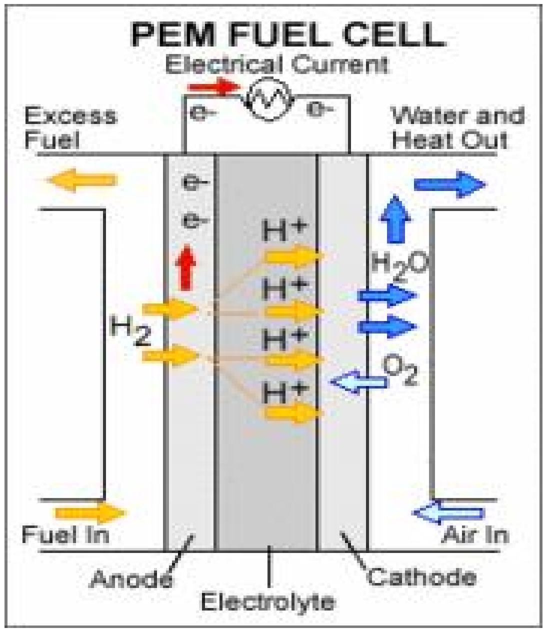


Figure 13. Proton Exchange Membrane Fuel Cell Chemistry

The power output produced by fuel cells is quite scalable, and the electrochemical oxidation process used by fuel cells to liberate potential energy is two to three times more efficient than combustion [26]. One major downside of thermodynamic combustion is the associated inefficiencies. Liberation of stored energy via a thermodynamic process, such as those used by the technologies mentioned so far, generates waste heat alongside the desired work output. Any energy invested in this waste heat puts the actual propulsion performance further from the theoretical performance limit [11].

One major issue in UAS and self-propelled vehicles in general is the issue of energy storage and energy density [6]. Fundamentally, this issue of a system's endurance being constrained by its capacity to carry its own energy source has motivated many new approaches in propulsion technology. As discussed in the previous technology example, a battery serves the need for a self-contained energy source: it generates a continuous supply of electrical power, and is rechargeable and completely self-contained (does not require an extant and continuous supply of external reactant). However, the physics of a battery dictates that an increase in energy storage capacity has a consequent size and weight penalty.

Essentially, a battery does two things in one: it houses the chemical reaction that produces electrical power, and houses the chemical reactants that participate in this reaction. This is comparable to a rocket, which houses a chemical reaction that produces the momentum exchange that accelerates it, and like a battery, houses the chemical reactants that participate in this reaction. A gas turbine engine has a similar output to a rocket, but while the combustion reaction that produces the pressure and high-velocity particles is also internal in the gas turbine engine, the reactants in this combustion are provided externally (e.g., environmental oxygenated air and petroleum fuel). In effect, a gas turbine engine is producing similar results as a rocket, yet benefiting from the energy density, availability, and desirable properties of the petroleum fuel by offloading the reactants. An analogy can be made by observing the relationship between rockets to gas turbine engines and batteries to fuel cells. A fuel cell produces similar results as a battery, yet benefit from the energy density, availability, and desirable properties of the hydrogen fuel by offloading the reactants.

The use of a PEMFC has advantages over a strictly battery-based system, such as better endurance and better replenishing characteristics (refill hydrogen tanks as opposed to recharging the battery); however, PEMFC has along with it many disadvantages. A dramatic increase in complexity occurs when using a PEMFC over a battery, and introduces many potential complications, which is discussed in section 5.8.6.

5.8.2 Representative Examples.

Tables 35-37 show examples of PEMFC-based systems.

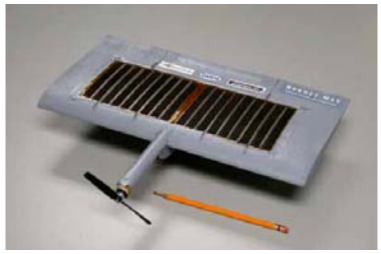
Table 35. Properties of the Protonex SpiderLion (PEMFC) [3, 22, and 27]

Protonex: SpiderLion 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Unavailable	Propulsion Class	Fuel Cell
Vehicle Gross Weight	2.5 kg (5.6 lb)	Propulsion Subclass	Proton Exchange Membrane
Payload Data	Unavailable	Propulsion Unit Make	Protonex ProCore UAV
Endurance Range/Time	3hr (15 g of hydrogen consumed) Goal: 8-24 hr	Propulsion Unit Weight	Fuel Cell 700 g Fuel Cartridge 1300 g Power System Volume 2799 cm^3
Ceiling	Unavailable	Power Output	95 W, 0.1 kW or 0.13 hp Goal: 1000 Wh/kg

The Hornet project is no longer an existing project; it was a research and development concept that has been retired. However, it is worth mention because "AeroVironment's Hornet became the first UA totally powered by hydrogen fuel when it flew in March 2003. Its fuel cell is shaped to also serve as the wing." [6]

Table 36. Properties of the AeroVironment Hornet (PEMFC) [6]

AeroVironment: Hornet



UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Length: 7 in. Wingspan: 15 in.	Propulsion Class	Fuel Cell
Vehicle Gross Weight	0.4 lb	Propulsion Subclass	Proton Exchange Membrane
Payload Data	0.1-lb capacity	Propulsion Unit Make	Unavailable
Endurance Range/Time	Unavailable	Propulsion Unit Weight	Unavailable
Ceiling	Unavailable	Power Output	Unavailable

Table 37. Properties of the Honda FC Stack (PEMFC) [28]

Honda: FC Stack

UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	N/A	Propulsion Class	Fuel Cell
Vehicle Gross Weight	N/A	Propulsion Subclass	Proton exchange membrane
Payload Data	N/A	Propulsion Unit Make	Honda FC Stack
Endurance Range/Time	N/A	Propulsion Unit Weight	2 x 48 kg (2 x 106 lb)
Ceiling	N/A	Power Output	86 kW (117 hp)

5.8.3 Category Advantages.

The advantages of the PEMFC-based systems are:

- Quiet
- Low-moving parts

- Zero-emission signature
- Higher-energy density than battery
- Reversible reaction has regenerative properties
- Uses electric motor as the prime mover; has advantages, including reliability, maintenance, control, and high-altitude operational benefits.

5.8.4 Category Disadvantages.

The disadvantages of the PEMFC-based systems are:

- Expensive (platinum catalyst)
- Pressurized components (inside fuel cell and liquid hydrogen)
- Complexity as compared to a battery system
- Catalyst sensitivity
- Humidity/water management
- New technology, still developing

5.8.5 Conceptual Decomposition.

Based on the proposed concept, the PEMFC-based system can be decomposed, as shown in table 38.

Table 38. Conceptual Decomposition of a PEMFC-Based System

Propulsion System	Conceptual Unit	Description
Proton Exchange Membrane Fuel Cell	Energy source	Molecular hydrogen internal energy relative to water
	Energy transformer	PEMFC creating a power source through ionization and electrochemical oxidation of molecular hydrogen
	Powerplant	Electrically driven motor
	Propulsion effecter	Propeller or fan unit driven directly or indirectly (geared) by motor shaft
	Control effecter	Hydrogen flow regulators, voltage/current boost regulators, analog/digital feedback control loops

5.8.6 Technical Issues.

The technical issues associated with a PEMFC are water management, catalyst pollution, corrosion, gas crossover, hydrogen pressurization, and temperature management (table 39).

Table 39. Technical Issues of a PEMFC-Based System

Technical Issue	Applicability to UAS Context
Water Management	The production of too much water as a waste product can drown the system. If the system gets too dry the electrolyte membrane can crack.
Catalyst Pollution	If the platinum catalyst is polluted with even a few parts per million of carbon dioxide molecules, the overall fuel cell efficiencies drop dramatically.
Corrosion	Corrosion of metal plates can create particles that damage the membrane and threaten output production.
Gas Crossover	Gas seeping past the membrane, known as gas crossover, can reduce efficiency and degrade performance.
Hydrogen Pressurization	High-pressure hydrogen fuel can suffer explosion and container fatigue from continuous thermal cycles of pressurization and depressurization.
Temperature Management	Fuel cells generate heat and, if left unaddressed, can affect operation.

5.9 PHOTOVOLTAICS.

5.9.1 Description.

The photoelectric effect is a quantum electronic phenomenon in which electrons are emitted from matter after the absorption of energy from electromagnetic radiation [29]. Solar cells convert the energy of electromagnetic radiation (at a frequency above the threshold frequency of the photoelectric material) into an electric power source by means of the photoelectric effect (figure 14). Solar cells and light-sensitive diodes also do this, but without ejecting electrons out of the material. In some semiconductors, light, even at visible frequencies, can excite electrons out of the valence band into the higher-energy conduction band, producing an electric current at a voltage.

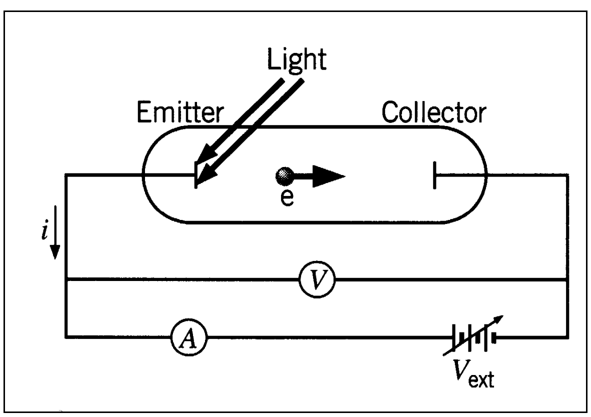


Figure 14. Photoelectric Effect

Solar power is the technology of obtaining usable electric power from sunlight. With sunlight as an effectively cost-free and inexhaustible resource, there is a growing demand to harness solar power for long-endurance systems to which it may be reasonably applied. Unfortunately, the intermittent availability of solar power (weather and/or daylight permitting) necessitates either short-term operation during peak sunlight hours, or some sort of auxiliary power storage.

Traditional approaches use a battery system as an energy storage system. An example of this is the AC Propulsion SoLong UAS. This aircraft is designed to be as light as possible to efficiently operate off the battery in low-sunlight conditions. During full-sunlight conditions, the solar panels generate enough power for both vehicle operation and battery charge recuperation. This arrangement has field-proven continuous flight of over 48 hours, and providing continuous sunlight is available during the day, claims are made that it can run indefinitely [18].

Solar-powered systems using photovoltaics are being explored for use in High-Altitude, Long Endurance (HALE) applications, "which hold the potential for unlimited flight" [30]. The renewable energy source of sunlight can power a reverse electrohydrolysis reaction, creating hydrogen fuel that can be used later to power a fuel cell when sunlight is not available [31]. Large surface areas are required to collect enough radiant solar energy to gain enough reserve power from available photovoltaic arrays at current efficiencies. Moreover, this need for enough sunlight intensity restricts flight of solar-based systems to operation in the mid-latitude regions [22].

5.9.2 Representative Examples.

Tables 40 and 41 show examples of photovoltaic-based systems.

Table 40. Properties of the AC Propulsion SoLong (Photovoltaic) [18]

AC Propulsion: SoLong

UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Wingspan 4.75 m	Propulsion Class	Photovoltaic
Vehicle Gross Weight	12.6 kg (28 lb)	Propulsion Subclass	Solar powered
Payload Data	Unavailable	Propulsion Unit Make	Sunpower A300 solar cells
Endurance Range/Time	48+ hr	Propulsion Unit Weight	Unavailable
Ceiling	8000 m	Power Output	Solar panel nominal power 225W

Table 41. Properties of the AeroVironment Helios (Photovoltaic) [23]

AeroVironment: Helios 			
UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	Wingspan 250 ft	Propulsion Class	Photovoltaic
Vehicle Gross Weight	1,800 lb	Propulsion Subclass	Solar powered
Payload Data	220-lb capacity	Propulsion Unit Make	Unavailable
Endurance Range/Time	Over the horizon/240 hr	Propulsion Unit Weight	Unavailable
Ceiling	96,863 ft	Power Output	Unavailable

5.9.3 Category Advantages.

The advantages of photovoltaic-based systems are:

- Primary energy source not carried onboard
- Silent
- No moving parts
- Can be used in regenerative fuel cell applications (reverse electrohydrolysis)
- Uses electric motor as the prime mover. Has advantages, including reliability, low maintenance, control, and high-altitude operational benefits.

5.9.4 Category Disadvantages.

The disadvantages of photovoltaic-based systems are:

- Expensive
- Poor efficiency
- Sensitivity to lighting conditions
    - Restricted to mid-latitude operation
    - Daytime use only
- Requires an energy storage buffer or supplementary system
- Reliability potential issue
- Durability an issue

5.9.5 Conceptual Decomposition.

Based on the proposed concept, the photovoltaic-based systems can be decomposed, as shown in table 42.

Table 42. Conceptual Decomposition of a Photovoltaic-Based System

Propulsion System	Conceptual Unit	Description
Photovoltaic-Based System	Energy source	Solar radiation
	Energy transformer	Superpositioned power-generating photovoltaic cells stimulated by the photoelectric effect
	Powerplant	Electrically driven motor
	Propulsion effecter	Propeller or fan unit driven directly or indirectly (geared) by motor shaft
	Control effecter	Voltage/current regulators, analog/digital feedback control loops

5.9.6 Technical Issues.

The technical issues of a photovoltaic-based system are light source dependency, array failure, and energy-buffering system requirement (table 43).

Table 43. Technical Issues of a Photovoltaic-Based System

Technical Issue	Applicability to UAS Context
Light Source Dependency	UAS may fly continuously without fatigue and therefore may allow intended operation above the restrictions of the NAS.
Array failure	Loss of primary energy source may not require an immediate forced landing (such as during night flight on battery backup), but detection mechanisms may be required even when the photovoltaic system is not in use.
Energy-Buffering System Requirement	Requirements for a fail-operational backup may add a irreconcilable weight penalty.

5.10 ULTRACAPACITOR.

5.10.1 Description.

A capacitor is an electrical component designed to store energy (in the form of an electric field) between a pair of closely spaced, mutually insulated conductors (figure 15) [32]. When a voltage is applied to the capacitor, electrostatic charges of equal magnitude and opposite polarity build up on each conductor. These devices are characterized by their ability to store an electrostatic charge, and the capacitance value is a relationship between how much charge will accumulate on the conductors for a given amount of electrical potential between them. They are used in electrical circuits as energy storage devices and can serve as electronic filters.

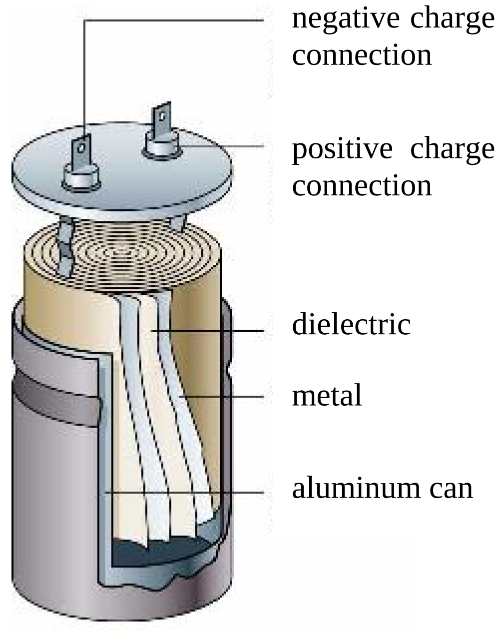


Figure 15. Basic Capacitor

The electrochemical process inside a battery imposes an internal resistance and therefore limits the rate of charge and discharge of the battery. High current drawn through this internal resistance can rapidly heat the vessel. Conversely, the mechanics of a capacitor is such that there is an almost negligible internal resistance (relative to a battery), minimizing the limit that it can accumulate and expel electrostatic potential energy. This makes capacitors essential for use as transient buffers in direct current (DC) applications and signal conditioners in alternate current (AC) applications [32].

An ultracapacitor is a specialized modern capacitor that has an unusually high energy density when compared to common capacitors (figure 16) [33]. Whereas size-limited normal capacitors only have sufficient charge capacities to provide power for time periods on the order of seconds, ultracapacitors can retain much greater energies for a comparable geometry. They are of particular interest in automotive applications for hybrid vehicles and are supplementary/buffering storage for electric vehicles [17].

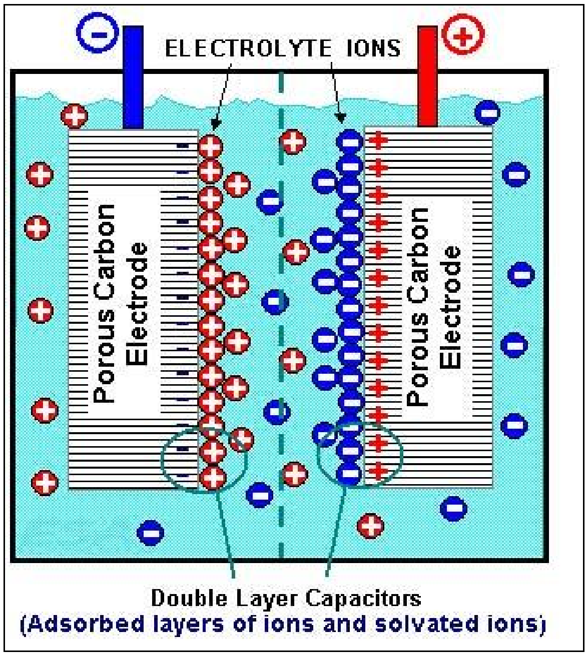


Figure 16. Ultracapacitor

The current capacity values render ultracapacitors less likely to be used as the primary means of an energy source, but instead as a buffering energy source. For example, if used with a fuel cell, the ultracapacitor may serve as a source of high power output transient current surges that the fuel cell is incapable of producing. In this scenario, an ultracapacitor may be chosen for this purpose over a battery due to its ability to output a high power charge quickly. There are already existing examples of this in applications such as the Honda FCX [28].

In the Honda FCX, energy reclaimed from the transduction of mechanical motion into electrical current in the magnetic braking system is stored in the ultracapacitor [28]. For aerospace applications, for example, a UAS may wish to the recover the energy lost when decreasing altitude. This might be done by using air speed to turn a motor shaft, which can then generate electrical energy similar to an alternator. The transient energy can be stored in an ultracapacitor and used later to power the vehicle or provide support for motor starts.

While there are no existing applications of ultracapacitors in existing UAS, their use in automotive applications provides a natural transition point into aerospace applications. More specifically, they are likely to be seen as a transient buffer in systems that have electrically based energy transformers. Additionally, ultracapacitors are being explored as replacements for batteries in public transportation applications due to their ability to be quickly recharged [34]. Promising new nanotechnology also may ultimately lead to ultracapacitor technology as an alternative or replacement for battery technology [35].

5.10.2 Representative Examples.

Tables 44 and 45 show examples of the ultracapacitor-based system.

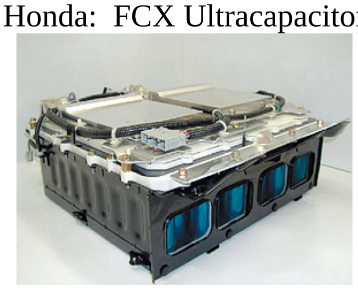
Table 44. Properties of the Maxwell BMOD0500-16.2V Ultracapacitor [36]

Maxwell: BMOD0500-16.2V Ultracapacitor

UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	N/A	Propulsion Class	Ultracapacitor
Vehicle Gross Weight	N/A	Propulsion Subclass	General use
Payload Data	N/A	Propulsion Unit Make	Maxwell BMOD0500-16.2V
Endurance Range/Time	N/A	Propulsion Unit Weight	Module weight 5.75 kg
Ceiling	N/A	Power Output	18.2 W*hr (3.17 W*hr/kg) 38,525 W peak (6700 W/kg)

Table 45. Properties of the Honda FCX Ultracapacitor [28]

Honda: FCX Ultracapacitor



UAS Characteristics		Propulsion Characteristics	
Vehicle Dimension	N/A	Propulsion Class	Ultracapacitor
Vehicle Gross Weight	N/A	Propulsion Subclass	Automotive
Payload Data	N/A	Propulsion Unit Make	Honda FCX system
Endurance Range/Time	N/A	Propulsion Unit Weight	Unavailable
Ceiling	N/A	Power Output	Power Density: 1750 W/kg Electrostatic charge capacity: 9.2 Farads

5.10.3 Category Advantages.

The advantages of the ultracapacitor-based systems are:

- Low internal resistance for high current densities (super-fast recharge)
- Silent
- Lightweight
- Simple
- No moving parts
- Low degradation over hundreds of thousands of charge/discharge cycles
- High responsiveness
- Uses electric motor as the prime mover. Has advantages, including reliability, maintenance, control and high-altitude operational benefits.

5.10.4 Category Disadvantages.

The disadvantages of the ultracapacitor-based systems are:

- No known existing UAS applications
- Expensive
- Complex internal chemistry
- Risk of high-power, short-circuit discharge
- Limited availability
- Limited endurance

5.10.5 Conceptual Decomposition.

Based on the proposed concept, the ultracapacitor-based system can be decomposed, as shown in table 46.

Table 46. Conceptual Decomposition of an Ultracapacitor-Based System

Propulsion System	Conceptual Unit	Description
Ultracapacitor-Based System	Energy source	Electrostatic potential within capacitor plates, charged by external source
	Energy transformer	Application of external load, liberating potential energy in the form of electric current
	Powerplant	Electrically driven DC motor
	Propulsion effecter	Propeller or fan unit driven directly or indirectly (geared) by motor shaft
	Control effecter	Voltage/current regulators, analog/digital feedback control loops

5.10.6 Technical Issues.

The technical issues associated with an ultracapacitor-based system are complex internal chemistry, endurance, short-circuit discharge, and reverse terminals (table 47).

Table 47. Technical Issues of an Ultracapacitor-Based System

Technical Issue	Applicability to UAS Context
Complex Internal Chemistry	Complex internal chemistry and materials
Endurance (Charge Capacity)	Ultracapacitors serving as a battery backup for redundancy in an electrically based UAS may have endurance issues.
Short-Circuit Discharge (Spark)	UAS circuitry, control, or electrically based powerplant may be short circuited if an uncontrolled discharge occurs.
Reverse Terminals (Explosion)	Reversed polarity of the terminals can cause capacitor to rupture or bloat.

6. SUMMARY.

A technology survey on UAS propulsion systems was conducted for this study. Survey results show that there are various types of propulsion systems with different power sources used in UAS. Their sizes range from less than an inch in diameter to fully certificated turbine engines as used in transport-category airplanes. New power sources, such as battery, solar, fuel cell, rocket fuel, etc., are often used to meet the operational needs. In summary, most of these propulsion systems, which are unique to UAS, are considered unconventional in reference to current regulatory standards. It is largely due to the unique operational objectives of UAS with specific mission requirements that are significantly different from manned aviation.

This document proposes a standard categorization scheme to describe a propulsion system. It proposes that a propulsion system, regardless of its types, is comprised of at least three of the five basic components: energy source, energy transformer, powerplant, propulsion effecter, and control effecter. Descriptions of each of these components and their interrelations were described. This categorization scheme was applied to describe the propulsion systems reviewed. Advantage and disadvantages for each category were summarized with examples of its applications to UAS are provided. The system was identified by the role it played in the conceptual context of a generic propulsion system. Technical issues were acknowledged and discussed with regard to their applicability to UAS in the NAS.

7. RECOMMENDATIONS.

It is anticipated that information generated from this study will bring to the foreground many types of propulsion systems that will need to be addressed by the regulatory standards. Various technical issues associated with each system are presented in this document. In response to the desire for UAS integration into the NAS, it is recommended that the current state of regulation be reexamined to embrace and cover the new issues brought into focus with the new technologies. Because of the complexity of these new propulsion systems and the large differences in sizes, utilizations of these propulsion systems will have the potential to impact the entire NAS.

Therefore, it is recommended that a systematic approach be established, of which regulatory related issues need to be addressed first. It is recommended that a regulatory gap analysis be performed, which would examine applicability of current regulatory standards in reference to the new propulsion technologies and identify specific technical areas that need to be studied further. A safety management system approach needs to be applied to assess potential risks of these new propulsion technologies in the NAS. Results from these risk assessments will enable the regulators to focus on key technical issues while establishing regulatory standards, policies, and guidance materials for the safety integration of UAS in the NAS.

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APPENDIX A—ADVANTAGES AND DISADVANTAGES SPREADSHEET

Table A-1. The Unmanned Aircraft System Propulsion Systems—Advantages and Disadvantages, Part 1

Propulsion System	Advantages	Disadvantages
Reciprocating Engines	▪ Widely understood technology o Benefits for maintenance and reparability ▪ Diesel engines support use of low volatility heavy fuels ▪ Potentially lightweight ▪ Potentially small sizes ▪ Supports forced-induction for high altitude use	▪ Vibration and noise ▪ Many moving parts ▪ Seal and lubrication requirements ▪ Cooling requirements o Efficiency loss in heat generated o Increased complexity o Fluid-based cooling systems need to be sealed and liquids separated o Adds a weight penalty ▪ Diesel engine has high compression ratios o In-flight restart becomes an issue o High transient vibrational characteristics transfers along power train
Rotary Engines	▪ Higher power output for similar displacement ▪ Iron rotor in aluminum housing reduces likelihood of engine seizure ▪ Lighter weight than legacy or CI engines ▪ Much quieter than reciprocating engines ▪ Lower vibration than reciprocating engines ▪ The most reduced parts count of any light aircraft engine. This relates to no valves, no heavy crankshaft, lighter propellers because of rotation vice reciprocation and much longer TBO of the engine. ▪ Overhaul cost is greatly reduced. ▪ Reliability expected to approach turbine standards. ▪ FADEC or DEM (Digital Engine Management) accounts for reduced fuel consumption to at or better than legacy engines.	▪ Liquid cooled engine adds to weight and complexity, failure modes ▪ 50% Higher fuel consumption than comparable diesel engines ▪ Higher EM and thermal signatures compared to diesel engine ▪ Limited information concerning technical success of Wankel rotary engines ▪ Potential difficulty meeting emission standards
Propeller Based systems	▪ Low engineering overhead ▪ Simpler control effecter (adjustments in speed and blade pitch) than a gas turbine engine ▪ Inexpensive as compared to more complex thrust based systems ▪ Propeller systems tend to have a quicker reaction to control changes than a gas turbine systems	▪ Strike hazard to personnel, object in environment ▪ Efficiency variations at different rotation speeds ▪ Rotation speed limited to about 2500 rpm by inefficiencies when the blade tips go supersonic ▪ Vibration sensitivities (subject to cracks)
Gas Turbine Engines	▪ High power density ▪ Tremendous thrust capability ▪ Not limited by sound barrier like the tips of propeller blades ▪ Decent efficiency at 30% load ▪ Insensitivity to fuel quality ▪ Can use of air bearings eliminates need for auxiliary lubricating fluid or oil	▪ Expensive ▪ Loud ▪ Jet wash ▪ Complexity ▪ Very high velocity rotation ▪ High internal temperatures
Rocket Propulsion	▪ High power density ▪ Mature, with long history of operation ▪ Self-contained energy source for use in low oxygen environments	▪ Inefficiencies at low speeds ▪ High rate of fuel usage; low endurance ▪ Complex control system ▪ Expensive guidance components

Table A-2. The Unmanned Aircraft System Propulsion Systems—Advantages and Disadvantages, Part 2

Propulsion System	Advantages	Disadvantages
Electric Motor Based systems	▪ Electrically powered ▪ Low maintenance ▪ Reliable ▪ Robust ▪ Less issues surrounding overheating as opposed to thermodynamic engines ▪ High torque ▪ Scalability ▪ Quiet	▪ Electromagnetic interference ▪ Requires large currents ▪ Potential sensitivity to water and other conductive liquids
Battery Based Systems	▪ Silent ▪ Lightweight ▪ Efficient (reduced levels of waste heat) ▪ No waste products ▪ Self-contained o No external reactants required o Reduced complexity ▪ No moving parts ▪ Rechargeable ▪ Uses electric motor as the prime mover; has advantages, including reliability, maintenance, control and high altitude operational benefits.	▪ Limited endurance ▪ Battery recharge o Delays due to current limits and recharge rates o Heating associated with rapid recharge o Battery discharge may be efficient, but recharge process is inefficient ▪ Heating do to internal resistance ▪ Performance sensitivity to environmental temperature conditions ▪ Hazardous chemicals (corrosive internal chemistry)
Proton Exchange Membrane Fuel Cell	▪ Quiet ▪ Low moving parts ▪ Zero emission signature ▪ Higher energy density than battery ▪ Reversible reaction has regenerative properties ▪ Uses electric motor as the prime mover; has advantages, including reliability, maintenance, control and high altitude operational benefits.	▪ Expensive (platinum catalyst) ▪ Pressurized components (inside FC and liquid Hydrogen) ▪ Complexity as compared to a battery system ▪ Catalyst sensitivity ▪ Humidity/water management ▪ New technology, still developing
Photovoltaics	▪ Primary energy source not carried onboard ▪ Silent ▪ No moving parts ▪ Can be used in regenerative fuel cell applications (reverse electrohydrolysis) ▪ Uses electric motor as the prime mover; has advantages, including reliability, low maintenance, control, and high altitude operational benefits.	▪ Expensive ▪ Poor efficiency ▪ Sensitivity to lighting conditions o Restricted to mid-latitude operation o Daytime use only ▪ Requires an energy storage buffer or supplementary system ▪ Reliability potential issue ▪ Durability an issue
Ultracapacitor	▪ Low internal resistance for high current densities (super-fast recharge) ▪ Silent ▪ Lightweight ▪ Simple ▪ No moving parts ▪ Low degradation over hundreds of thousands of charge/discharge cycles ▪ High responsiveness ▪ Uses electric motor as the prime mover; has advantages, including reliability, maintenance, control and high altitude operational benefits.	▪ No known existing UAS applications ▪ Expensive ▪ Complex internal chemistry ▪ Risk of high power short circuit discharge ▪ Limited availability ▪ Limited endurance (to date)

APPENDIX B—ENUMERATION SPREADSHEET

Figure B-1. The Unmanned Aircraft System Data Comparison Spreadsheet

UAS	Manufacturer	Vehicle Dimension	Vehicle Gross Weight	Payload Data	Endurance Range/Time	Ceiling	Propulsion Class	Propulsion Subclass	Propulsion Unit Make	Propulsion Unit Weight	Power Output
Aladin	EMT	Wingspan: 4.9 ft	6.6 lb	Unavailable	6 nm/1 hr	500 ft	Battery	Unavailable	Unavailable	Unavailable	Unavailable
BATCAM	ARA	Length: 24 in. Wingspan: 21 in.	0.84 lb	0.09-lb capacity	1.6 nm/18 min	1,000 ft	Battery	Unavailable	Unavailable	Unavailable	Unavailable
CL-289	Bombardier	Wingspan: 4.3 ft	650 lb	75-lb capacity	108 nm/0.5 hr	3,900 ft	Gas turbine engine	Turbojet	KHD T117	Engine: 51 lbs (23 kg)	236-lb thrust
Cormorant Project	Lockheed Martin	Length: 19 ft Wingspan: 16 ft	9,000 lb	1,000 lb	400-500 nm/3 hr	35,000 ft	TBD	TBD	TBD	TBD	3,000-lb thrust RATO
Cypher	Sikorsky	Diameter: 6.5 ft	250 lb	50-lb capacity	36 nm/3 hr	8,000 ft	Wankel Rotary engine	Single rotor	UEL AR-801, 294 cc	Engine: 43 lb (cf. AR-801 spec. sheet)	40 bhp @ 6,000 rpm, 51 bhp @ 8,000 rpm
Desert Hawk	Lockheed Martin	Length: 34 in. Wingspan: 2 in.	3.5 kg (7 lb)	Color CCD or infrared cameras	6 nm/1 hr	500 ft	Battery	Unavailable	Unavailable	Unavailable	Unavailable
Helios	AeroVironment	Wingspan: 250 ft	1,800 lb	220-lb capacity	“Over the horizon”/240 hr	96,863 ft	Photovoltaic	Solar powered	Unavailable	Unavailable	Unavailable
Hornet	AeroVironment	Length: 7 in. Wingspan: 15 in.	0.4 lb	0.1-lb capacity	Unavailable	Unavailable	Fuel Cell	Proton Exchange Membrane	Unavailable	Unavailable	Unavailable

Figure B-1. The Unmanned Aircraft System Data Comparison Spreadsheet (Continued)

UAS	Manufacturer	Vehicle Dimension	Vehicle Gross Weight	Payload Data	Endurance Range/Time	Ceiling	Propulsion Class	Propulsion Subclass	Propulsion Unit Make	Propulsion Unit Weight	Power Output
Insitu/Boeing	ScanEagle A	Length: 1.19 m (3.9 ft) Wingspan: 3.05 m (10.0 ft)	40 lb	Electro-optical or an infrared camera	15 hr	16,000 ft	Reciprocating piston engine	1-cylinder, 2-stroke, also Heavy fuel variant	3W-28i, also Sonex Combustion System heavy fuel modification	Engine: 2.67 lb	2.75 hp (2 kW)
MAV	Honeywell	Diameter: 15 in.	15 lb	2-lb capacity	6 nm/40 min	10,500 ft	Reciprocating piston engine	Heavy fuel engine	RCV 60 cc	5.5 lb	4.2 bhp @ 8200 rpm
MQ-1B Predator	General Atomics	Length: 26.7 ft Wingspan: 48.7 ft	2,250 lb	450-lb capacity	500 nm/ Over 24 hrs	25,000 ft	Reciprocating piston Engine	4-stroke	Rotax 914F	Engine: 150 lb	115 hp @ 5800 rpm
Predator B	General Atomics	Wingspan: 66 ft	10,000 lb	800-lb internal capacity 3,000-lb external capacity	30+ hr	50,000 ft	Gas turbine engine	Turboprop	TPE-331-10T	Unavailable	700 shp
RQ-2B Pioneer	Pioneer UAV	Length: 14 ft Wingspan: 17 ft	452 lb	75-lb capacity	100 nm/5hr	15,000 ft	Reciprocating piston engine	2-cylinder 2-stroke	Sachs SF 350	Unavailable	26 hp
RQ-4A Global Hawk	Northrop-Grumman	Length: 44.4 ft Wingspan: 116.2 ft	26,750 lb	1,950-lb capacity	5,400 nm/32 hr	65,000 ft	Gas turbine engine	Turbofan	Rolls Royce AE-3007H	Engine: 1,586 lb	8290-lb Thrust
RQ-5A Hunter	Northrop-Grumman	Length: 22.6 ft Wingspan: 29.2 ft	1,620 lb	200-lb capacity	144 nm/11.6 hr	15,000 ft	Reciprocating piston engine	4-stroke, heavy fuel	Moto Guzzi	Unavailable	57 hp (44 kW)

Figure B-1. The Unmanned Aircraft System Data Comparison Spreadsheet (Continued)

UAS	Manufacturer	Vehicle Dimension	Vehicle Gross Weight	Payload Data	Endurance Range/Time	Ceiling	Propulsion Class	Propulsion Subclass	Propulsion Unit Make	Propulsion Unit Weight	Power Output
RQ-7A Shadow 200	AAI	Length: 11.2 ft Wingspan: 12.8 ft	327 lb	60-lb capacity	68 nm/5 hr	14,000 ft	Wankel Rotary engine	Single rotor	UEL AR-741, 208 cc	Engine: 23.5 lb	38 bhp @ 7800 rpm
SoLong	AC Propulsion	Wingspan: 4.75 m	12.6 kg (28 lb)	Unavailable	48+ hr	8,000 m	Photovoltaic	Solar powered	Sunpower A300 solar cells	Unavailable	Solar panel nom. Power 225W
SpiderLion	NRL/Protonex	Unavailable	2.5 kg (5.6 lb)	Unavailable	3hr (15 g of hydrogen consumed) Goal: 8-24 hr	Unavailable	Fuel Cell	Proton Exchange Membrane	Protonex ProCore UAV	Fuel Cell 700 g Fuel Cartridge 1300 g Power System Volume 2799 cm3	95 W, 0.1 kW or 0.13 hp Goal: 1,000 Wh/kg
Wasp	AeroVironment	Length: 8 in. Wingspan: 13 in.	0.4 lb	0.1-lb capacity Daylight cameras with real time video downlink	5 nm/60 min	1,200 ft	Battery	Proprietary	Proprietary	Proprietary	Proprietary

RCV = Rotary cylinder valve
UAV = Unmanned aviation vehicle